Tevatron Results on Electroweak, Higgs, and Bottom Quark Physics

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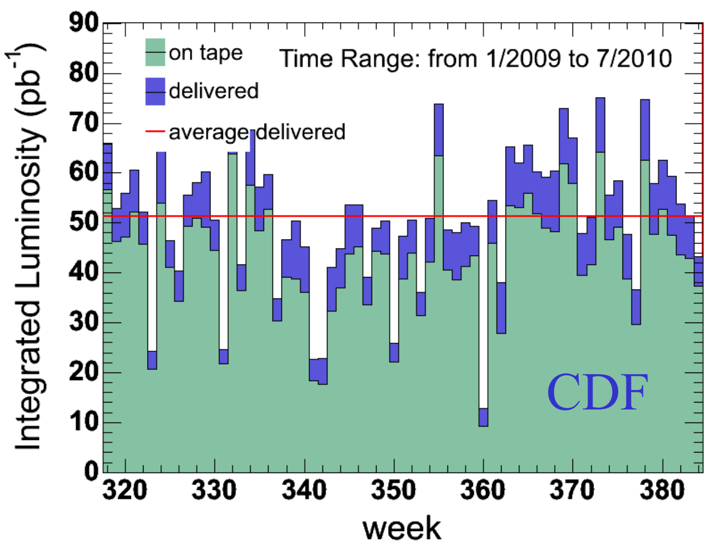
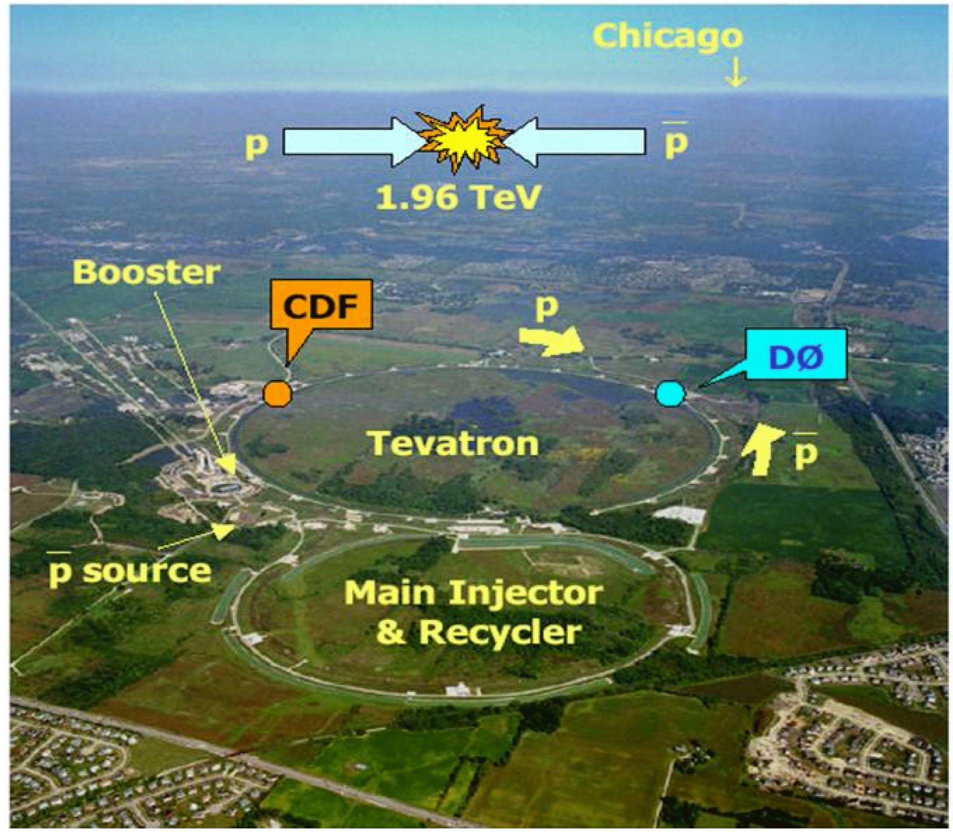
August 20th, 2010
HCP Summer School

W and Z Boson Factory

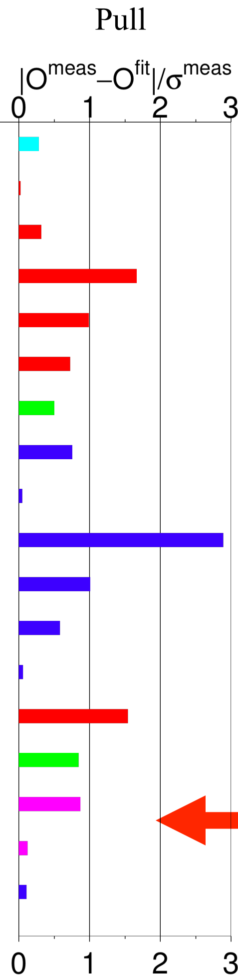




Mode	Events/Week/Exp. (before trigger & cuts)
$W \to e\nu$	~125,000
$Z \to ee$	~12,500

Precision EWK Measurements

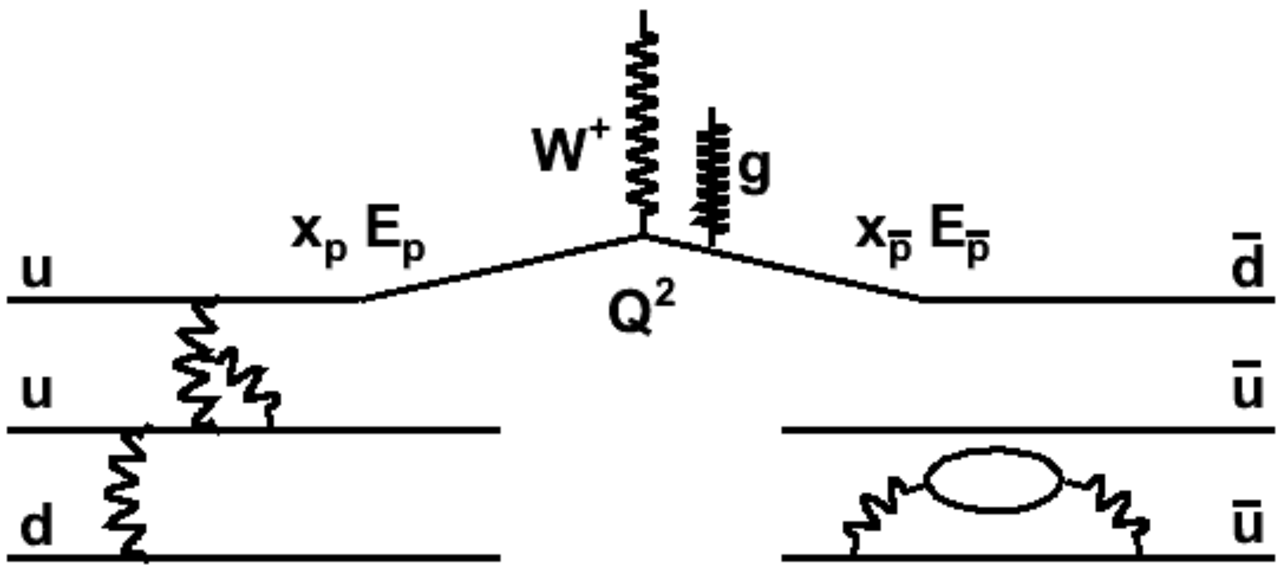
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2



August 2009

- Many high precision measurements of EWK observables from LEP and SLD
- A total of roughly 17 million Z events were collected by the four LEP experiments
- In 8 fb^{-1} of running the two Tevatron experiments will collect a similar number of W events

QCD Boson Production



$$\sigma = \sum_{ab} \int dQ\ \delta(Q - 2E_p\sqrt{x_p x_{\bar{p}}}) \int dx_p\ f_a(x_p, Q) \int dx_{\bar{p}}\ f_b(x_{\bar{p}}, Q)\ \sigma(\hat{Q})$$

Sum over quarks, gluons

Kinematic constraint

Parton distribution functions

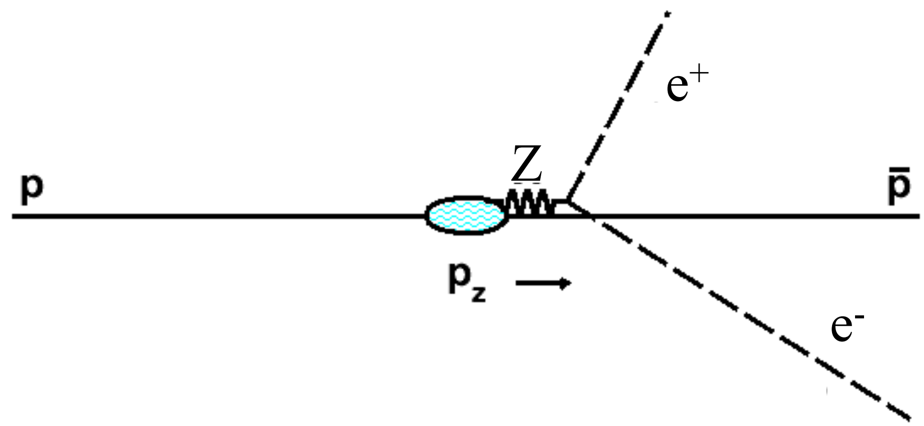
Calculable hard scattering cross section

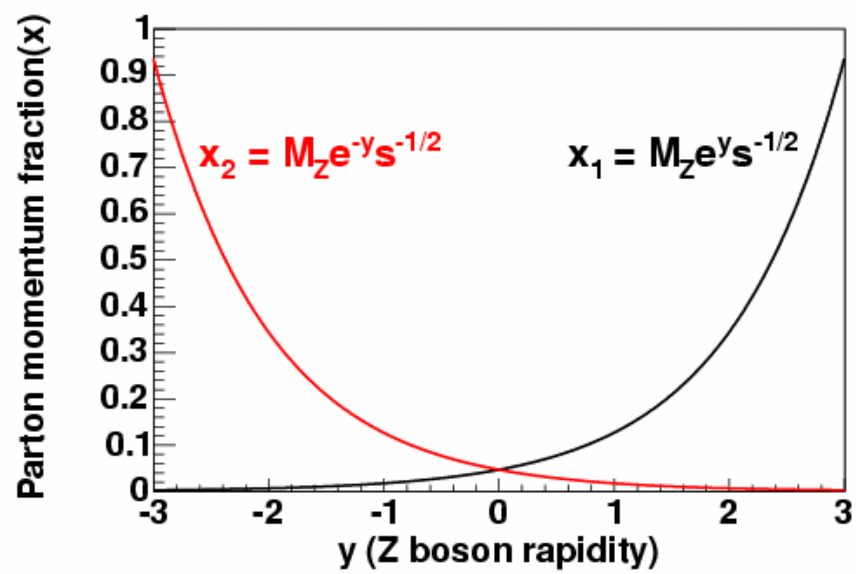
Differential Cross Sections

$$y = 0.5 \ln\left[\frac{E + p_z}{E - p_z}\right]$$

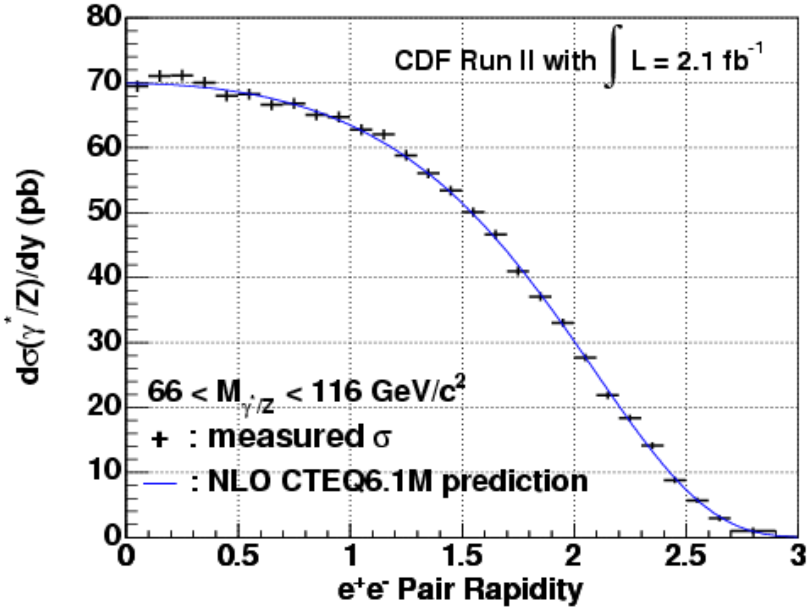
$$y = 0.5 \ln\left[\frac{x_p}{x_{\bar{p}}}\right]$$

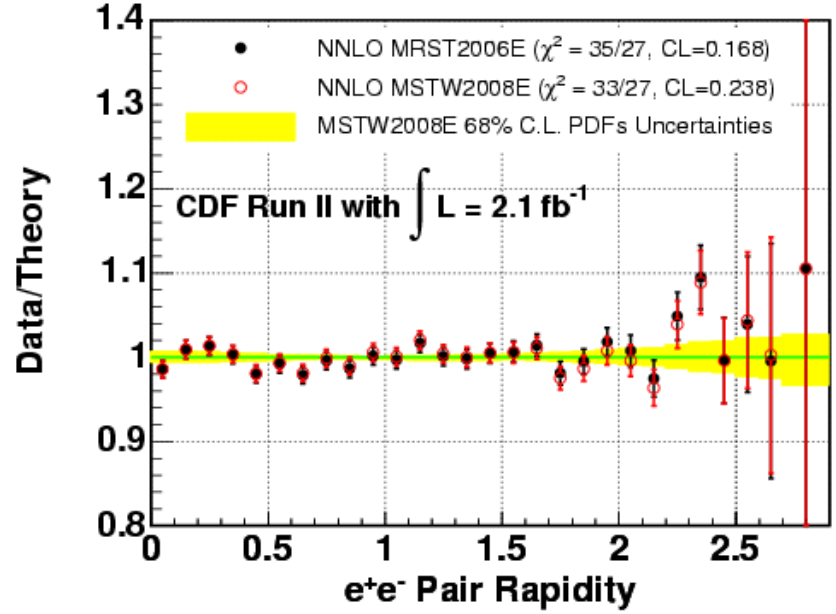
- Relative sizes of x_p, $x_{\bar{p}}$ determine the longitudinal momentum of boson





dσ/dy Measurement



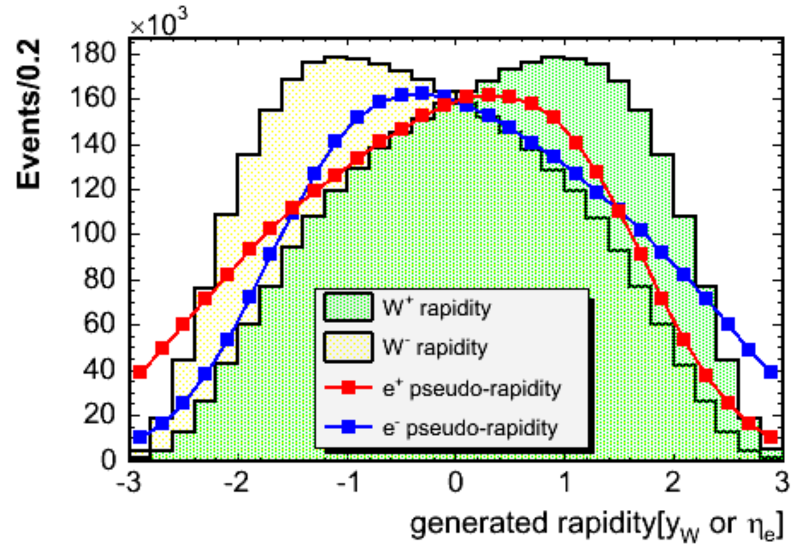


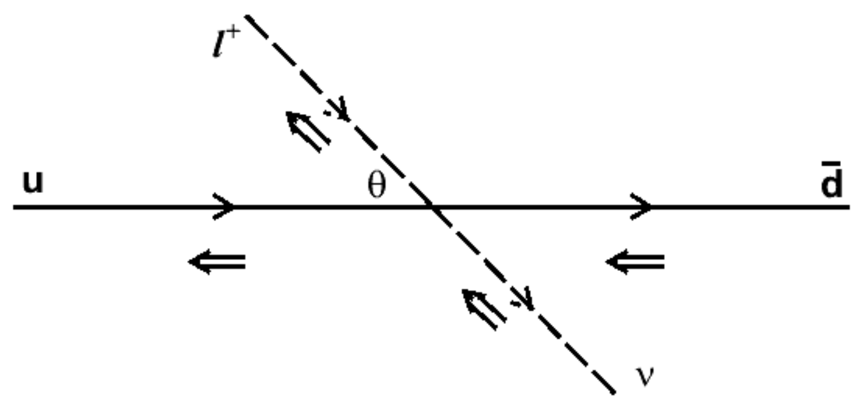
- Measurements at high rapidity are statistics limited
- Potential increased constraints on PDF models using full Tevatron data samples

W Asymmetry

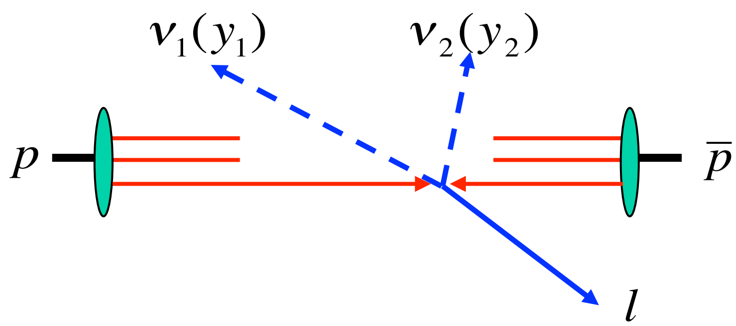
- Asymmetric u,d quark momentum distributions within proton lead to asymmetric W^+,W^- rapidity distributions
- V-A decay of W boson reduces the observable asymmetry in the lepton rapidity distributions

$$d\sigma/d\theta \propto (1 + \cos\theta)^2$$

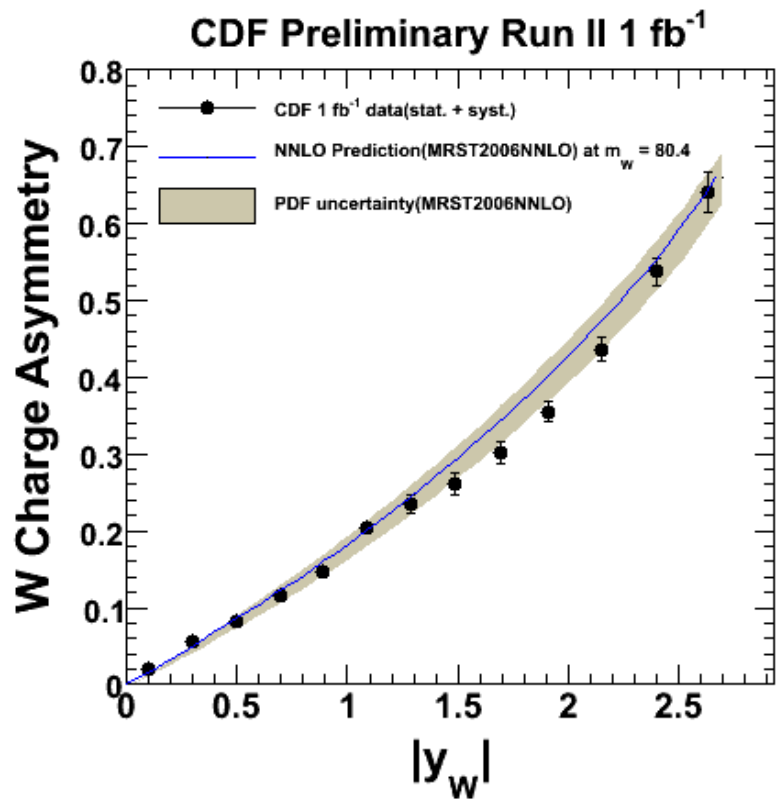




New Asymmetry Measurements

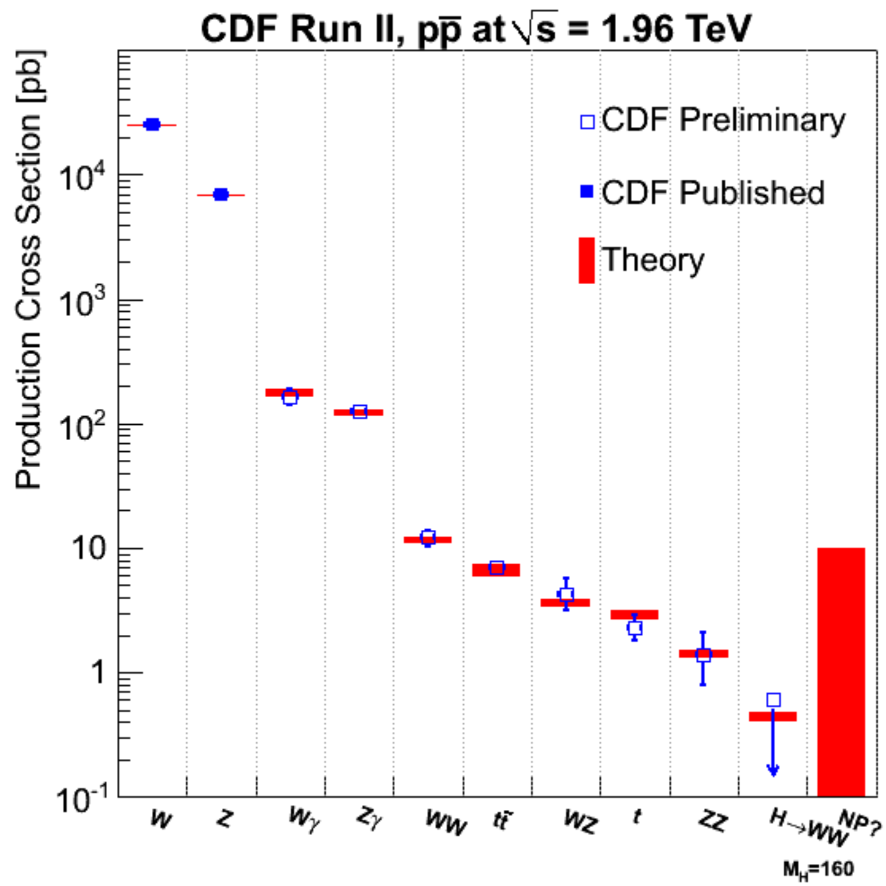


- Reconstruct W production asymmetry $A(y_W)$ directly
- Two kinematic solutions using M_W constraint
- Weight solutions taking into account production & decay
- Resolve dependence on y_W iteratively



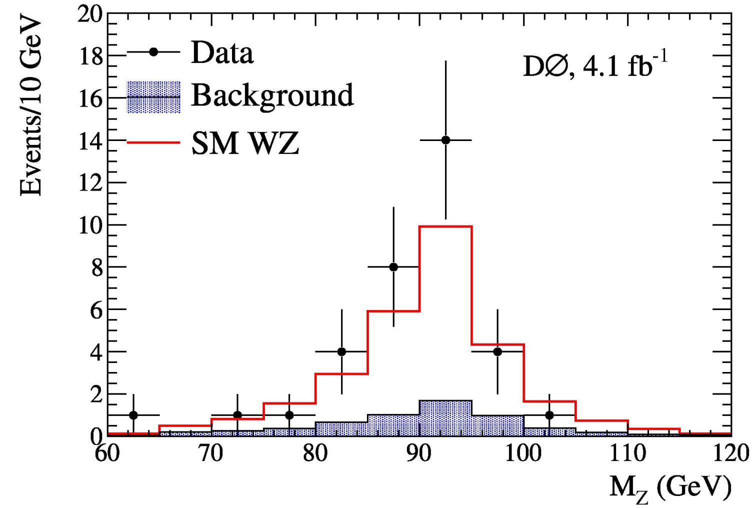
Diboson Production

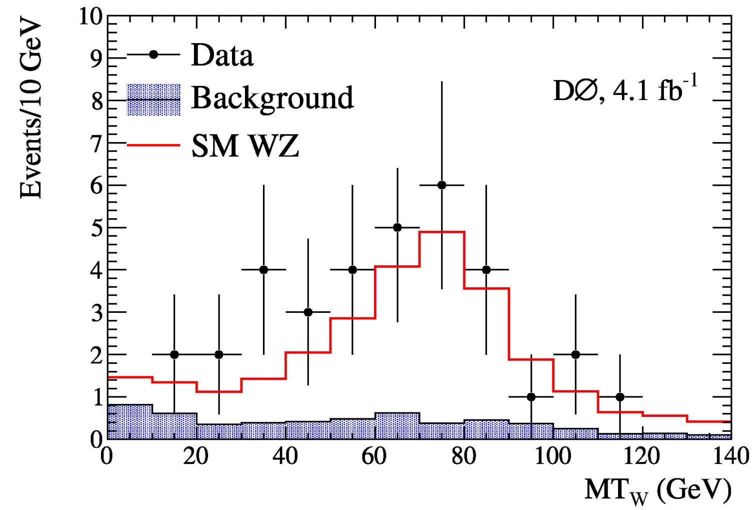
- High luminosity samples allow for measurements of low cross section processes
- D0 and CDF have observed WW, WZ, and ZZ production via leptonic decay channels
- Also, first observations of WW/WZ production in the semi-leptonic decay channel
- These measurements are critical for validating our Higgs search techniques



WZ Production

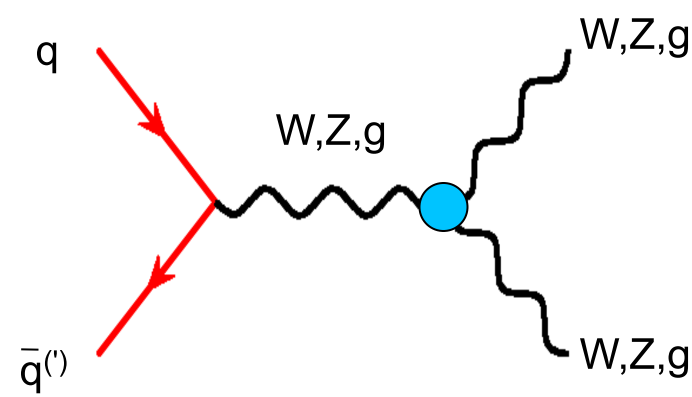
- Recent measurement of WZ production from D0 based on 4.1 fb^{-1}
- Final state of three high p_T leptons and large missing E_T
- Observe 34 candidate events with an expectation of 6.0 ± 0.4 background events
- Measured cross section of 3.90 ± 0.98 pb agrees well with SM calculation





Diboson Couplings

- Probe non-Abelian nature of $SU(2)_L \otimes U(1)_Y$ via gauge boson self-interactions
- Production is sensitive to potential new physics appearing in the tri-linear gauge couplings
- For simplicity, parameterize new physics contributions in terms of effect on individual terms within the interaction Lagrangian ($g_{SM} = 1$, $\kappa_{SM} = 1$, $\lambda_{SM} = 0$)

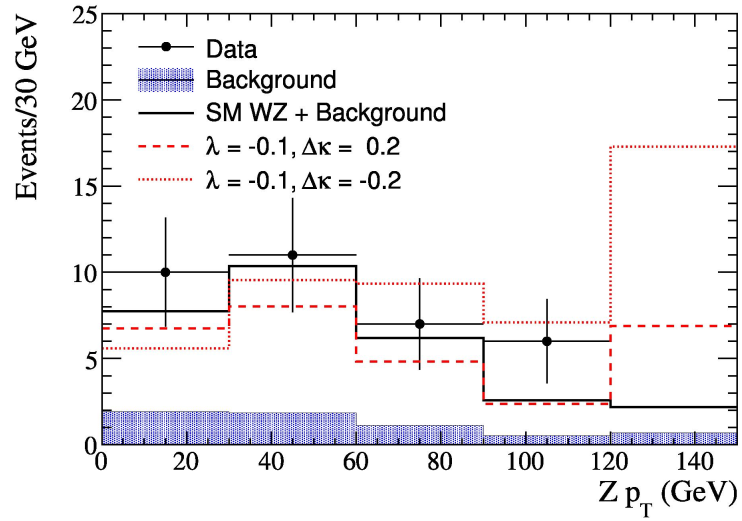


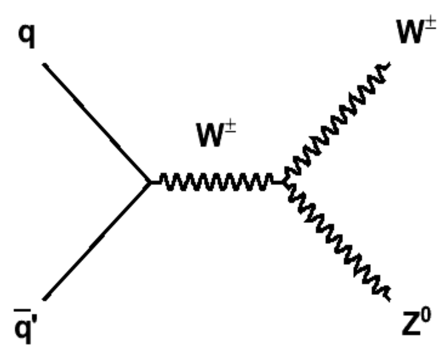
$$q\bar{q}' \to W^* \to W\gamma \ : WW\gamma \text{ only}$$
$$q\bar{q}' \to W^* \to WZ \ : WWZ \text{ only}$$
$$q\bar{q} \to Z/\gamma^* \to WW \ : WW\gamma\,,\, WWZ$$
$$q\bar{q} \to Z/\gamma^* \to Z\gamma \ : \boxed{ZZ\gamma\,,\, Z\gamma\gamma}$$
$$q\bar{q} \to Z/\gamma^* \to ZZ \ : \boxed{ZZ\gamma\,,\, ZZZ}$$

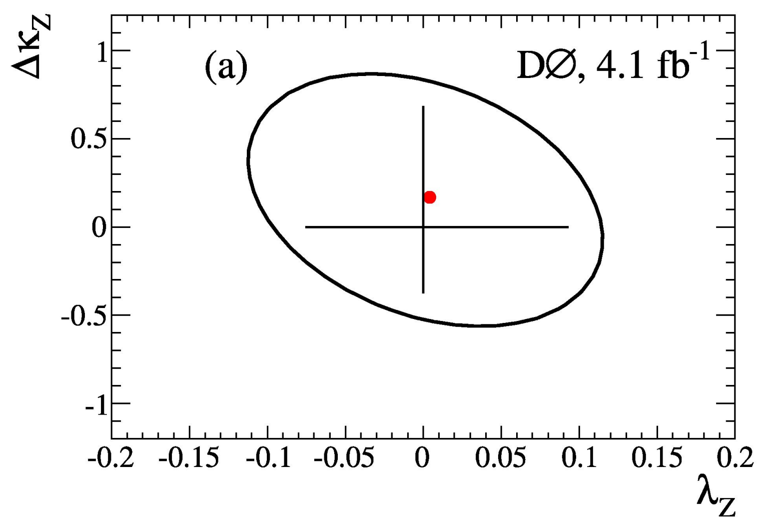
Absent in SM

Anomalous Coupling Limits

- WZ production involves a single tri-linear gauge coupling not accessible at LEP
- Allows for measurement of WWZ coupling independent of WWγ coupling



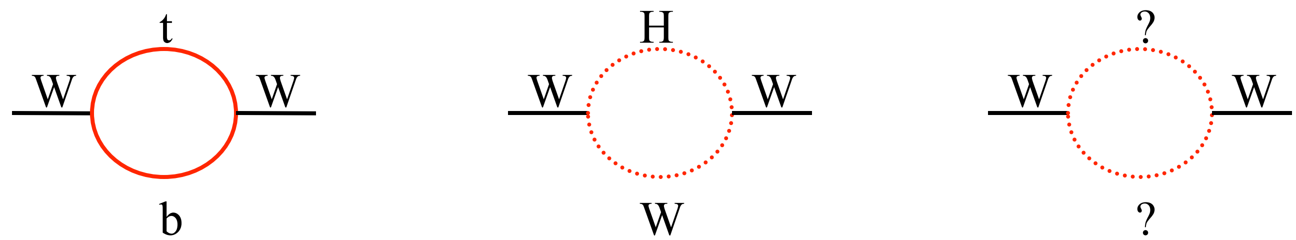




$-0.075 < \lambda_Z < 0.093$

$-0.027 < \Delta\kappa_Z < 0.080$

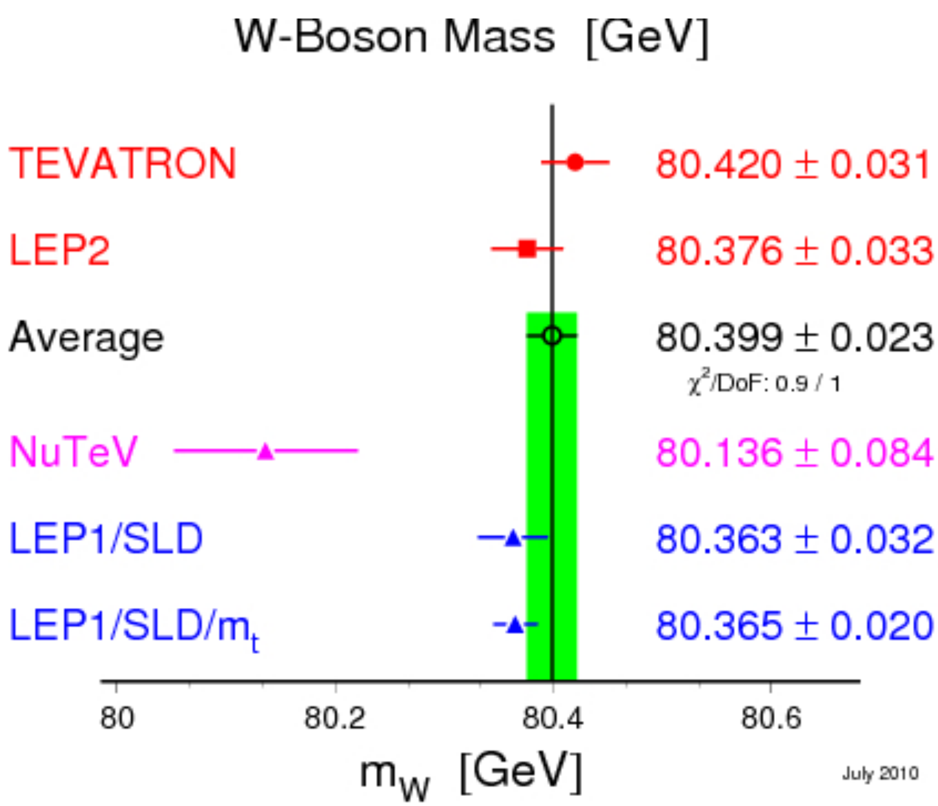
W Boson Mass



$\Delta M_W \propto M^2_{top}$ $\Delta M_W \propto \ln M_H$ New Physics

- Self-energy corrections to the W mass depend on the mass of the top quark and Higgs boson.

Current W Mass Results

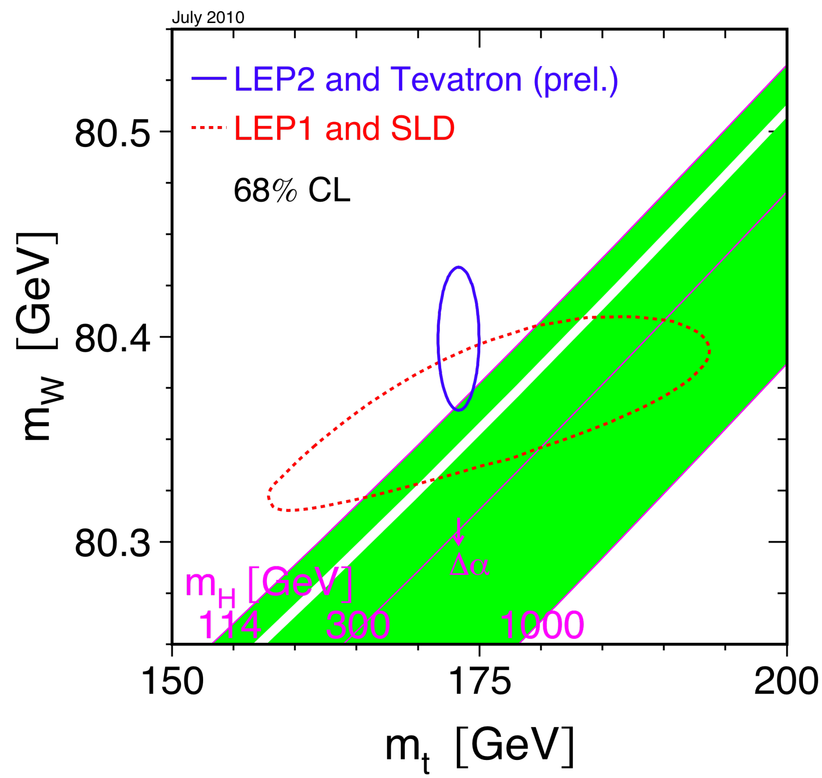


- Current level of precision ~ 0.03%
- This uncertainty is roughly an order of magnitude higher than that for the Z boson mass

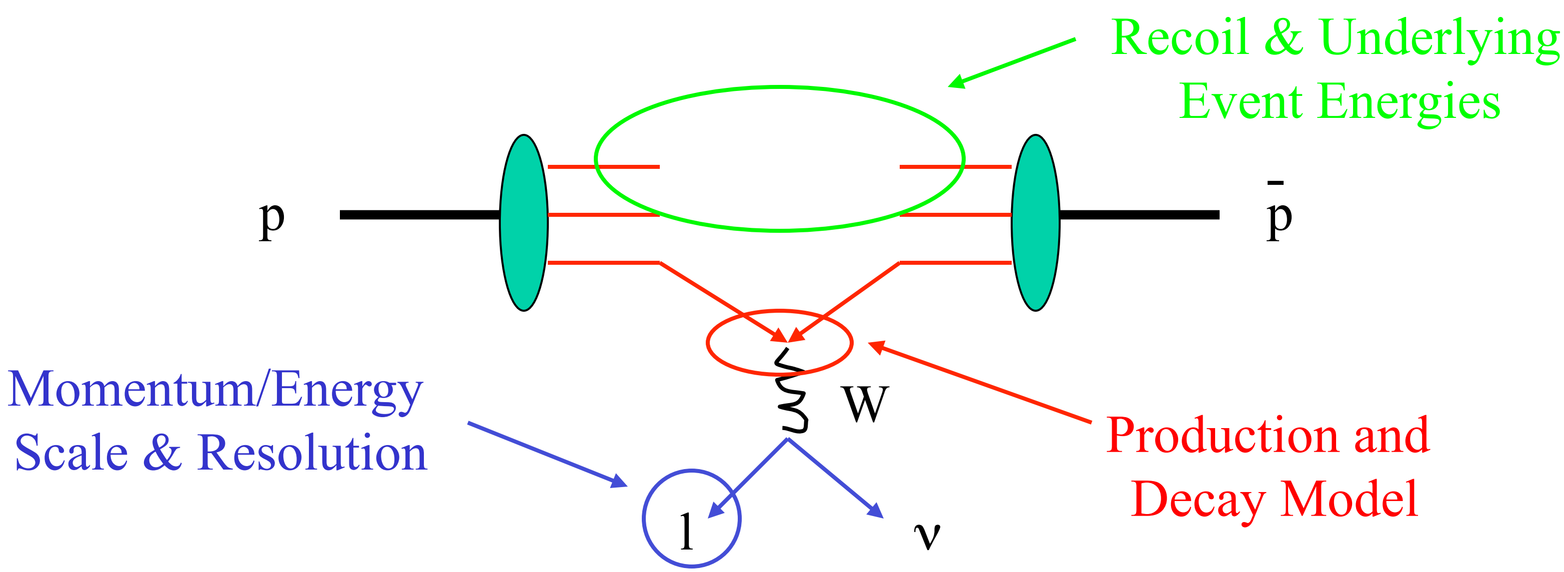
$M_Z = 91.1876 \pm 0.0021$

Constraints on Higgs Mass

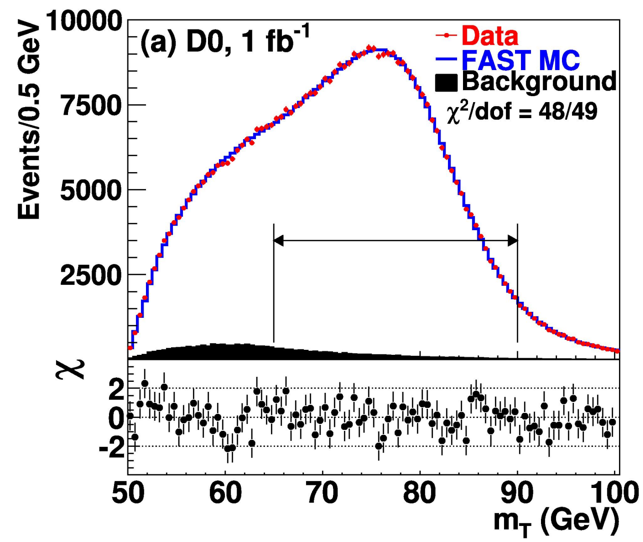
- To obtain equivalent constraint on M_H
  - $\Delta M_{top} \sim 1.1$ GeV/c^2, $\sim 0.6\%$ on M_{top}
  - $\Delta M_W \sim 20$ MeV/c^2, $\sim 0.02\%$ on M_W



W Mass Measurement



- Requires a detailed understanding (~10 MeV) of all aspects of W boson production and detection



$W \rightarrow e\nu$

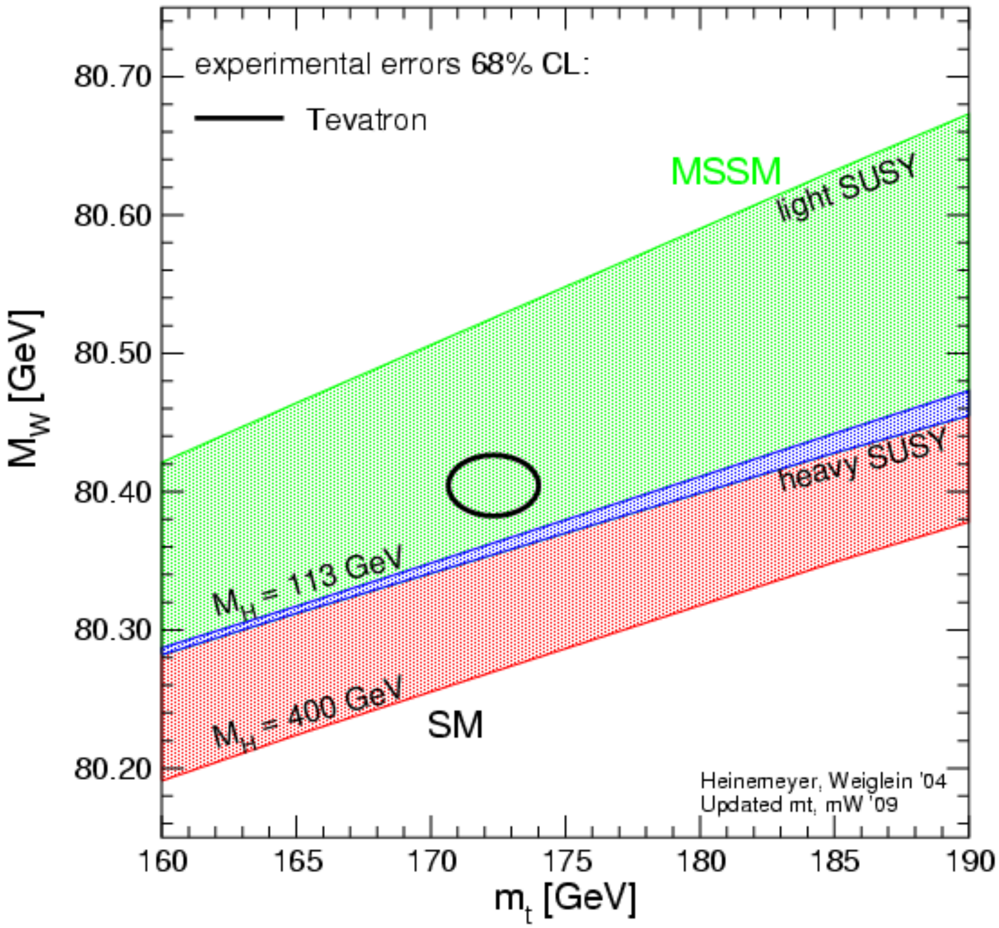
W Mass Uncertainties

- CDF systematic uncertainties for 200 pb^{-1}
- Combined channel total uncertainty of 48 MeV
- New analysis based on 2 fb^{-1} currently in progress. Expect to reduce uncertainty by factor of two

Systematic [MeV]	Electrons	Muons	Common
Lepton Energy Scale and Resolution	31	17	17
Recoil Scale and Resolution	14	12	12
Backgrounds	8	9	0
Production and Decay Model	16	17	16
Statistics	48	54	0
Total	62	60	26

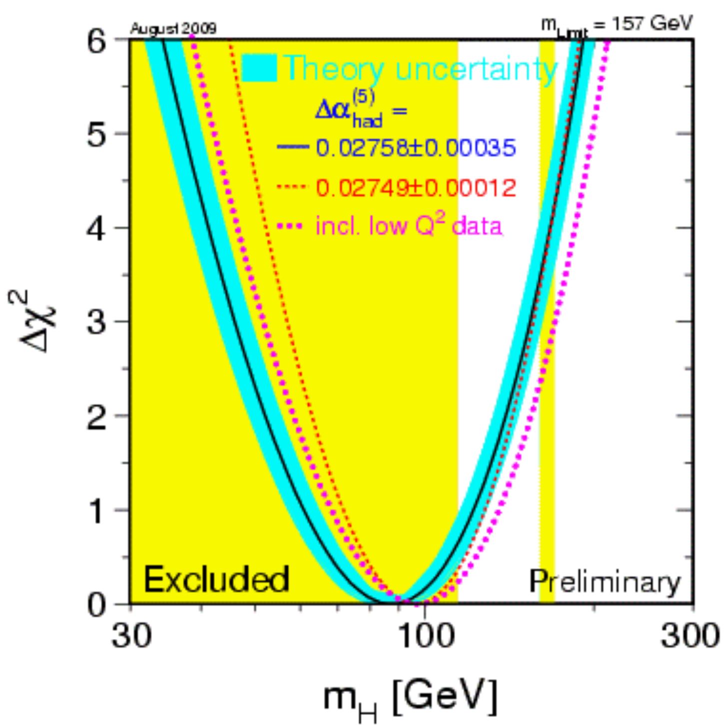
Ultimate Tevatron Constraints

- Potential constraints on M_H based on 8 fb^{-1} of data per experiment
- Use to differentiate between a SM or SUSY-like Higgs
- Provides a test of the theories if a Higgs boson is discovered in the interim



Higgs Boson in SM

- Combination of direct constraints from LEP and indirect constraints from precision EWK measurements indicates m_H in range accessible to Tevatron



LEP direct constraints : $m_H > 114.4$ GeV/c^2

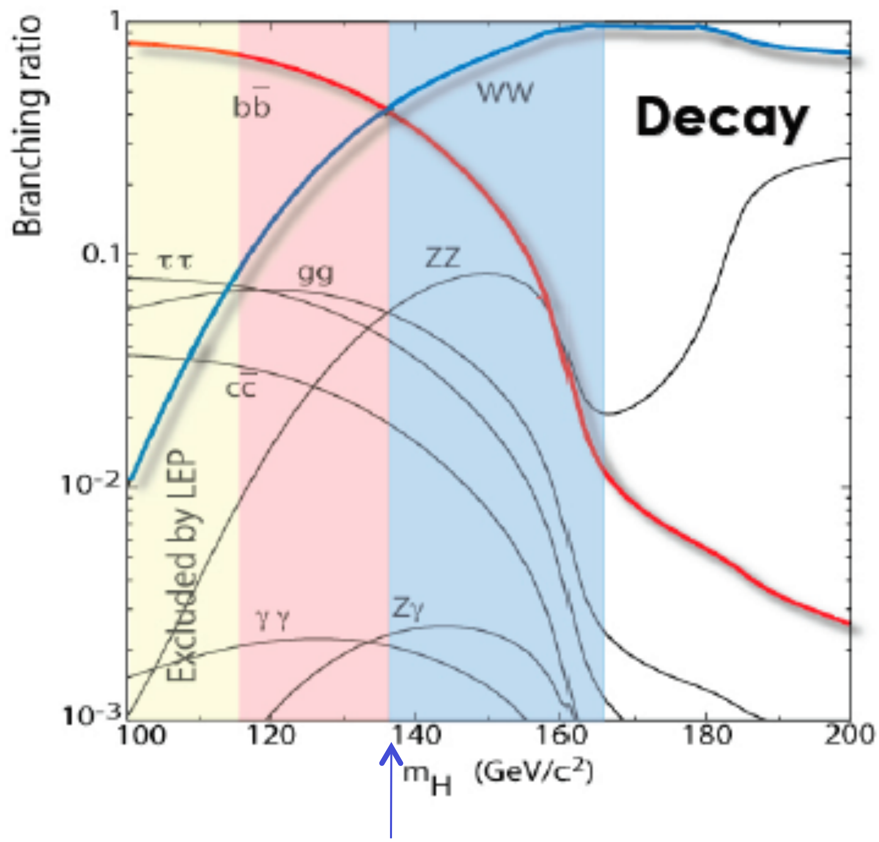
Indirect constraints : $m_H < 158$ GeV/c^2

Combined constraints : $m_H < 185$ GeV/c^2

Excluded by direct searches at LEP

Potentially observable at Tevatron

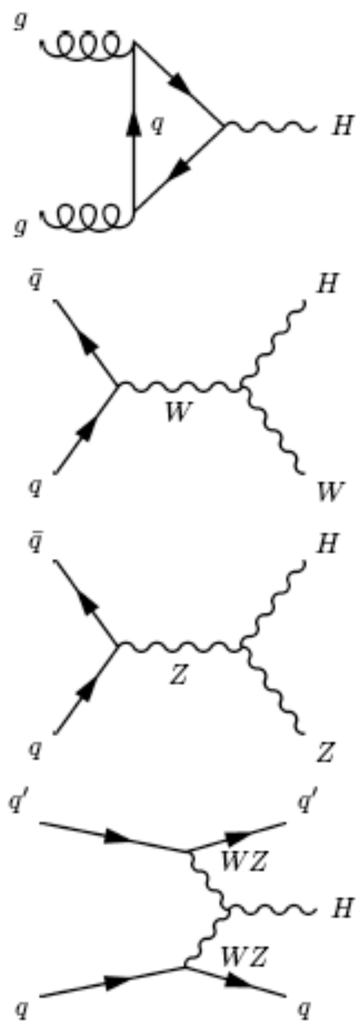
Higgs Decay

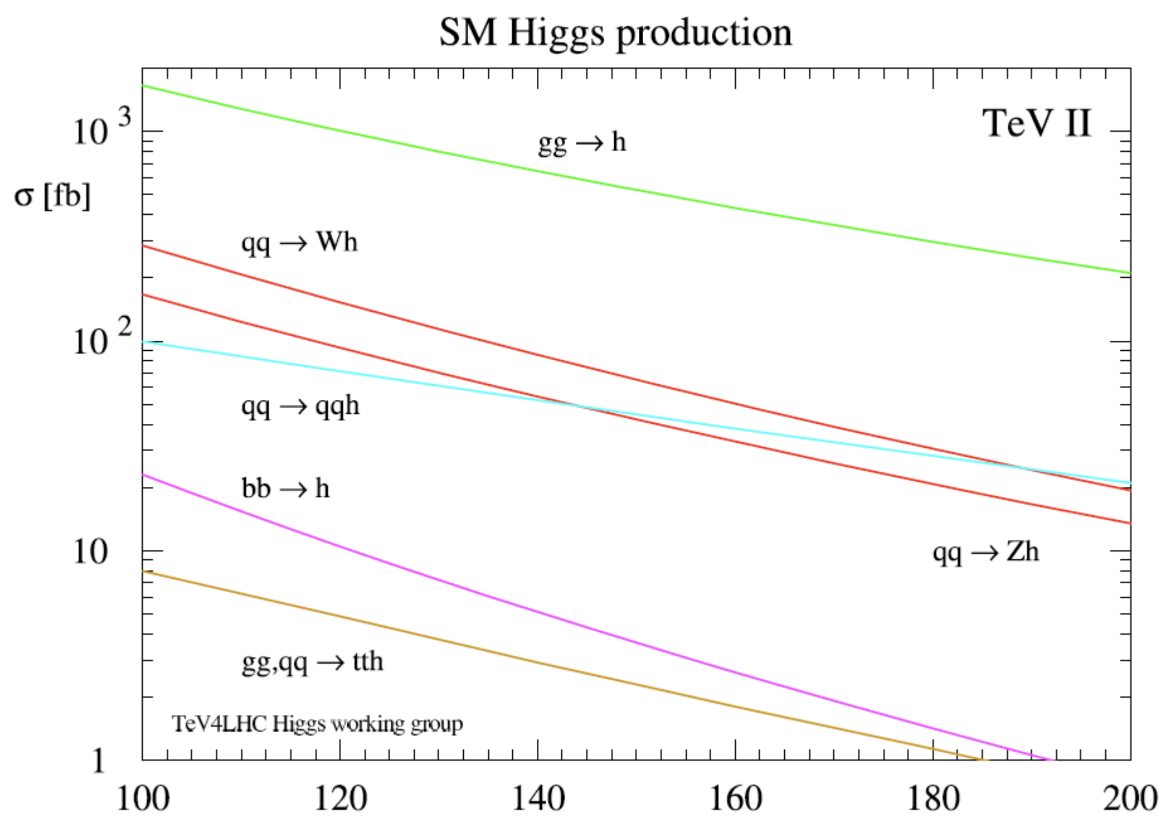


Cross-Over Point
($m_H \sim 135$ GeV)

- Low Mass
  - Focus on H→bb
  - Also search in H→ττ and H→γγ (important LHC channels)
- High Mass
  - Focus on H→WW
  - Plan to incorporate H→ZZ decays in future (also an important channel at LHC)

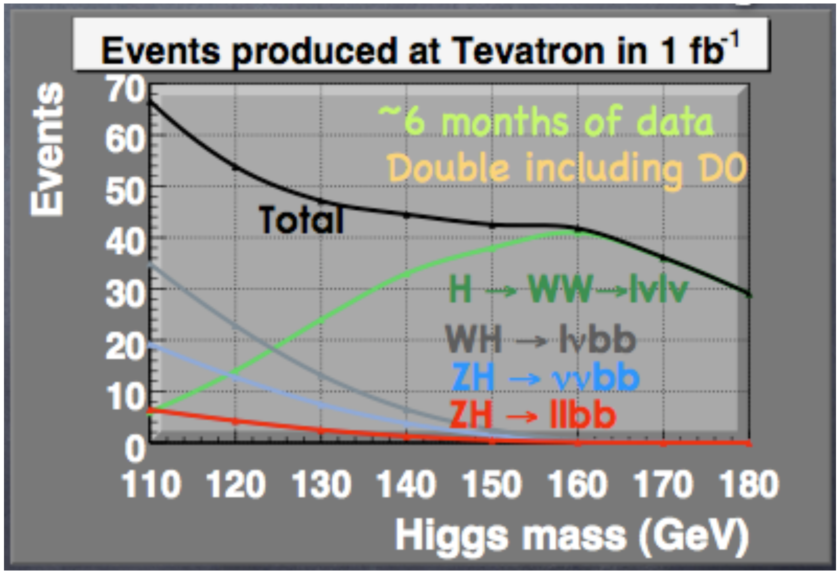
Higgs Production at Tevatron





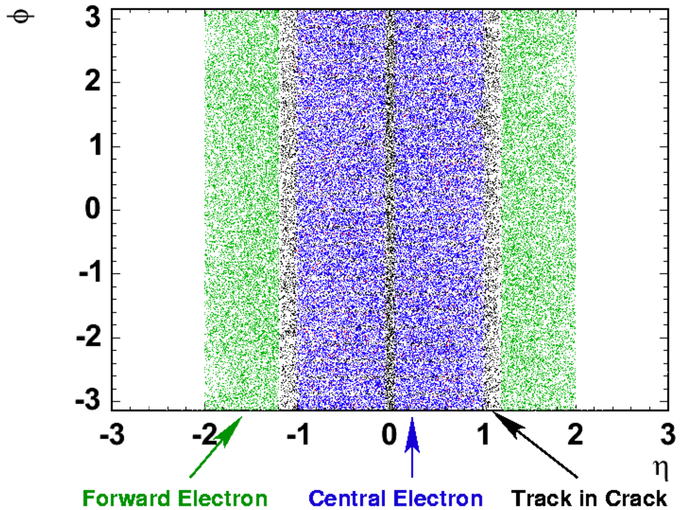
General Analysis Approach

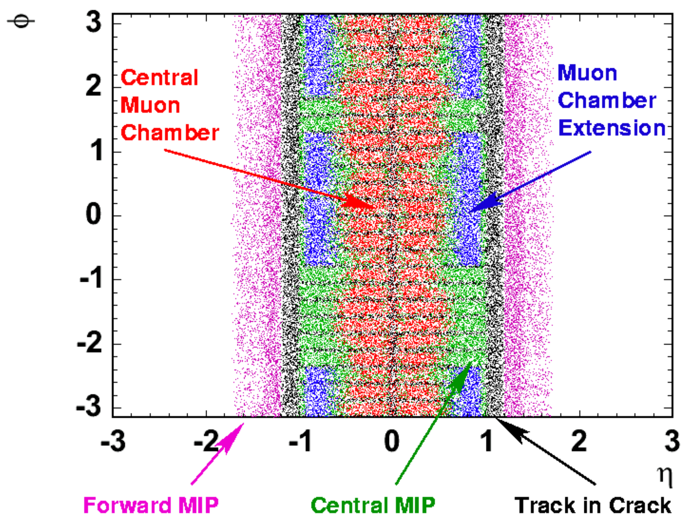
- Step #1 : Select an inclusive event sample that maximizes the acceptance for a potential Higgs signal
- Step #2 : Carefully model all backgrounds and cross check using control regions in data
- Step #3 : Use advanced analysis tools to separate signal from background based on event kinematics



High Mass Searches

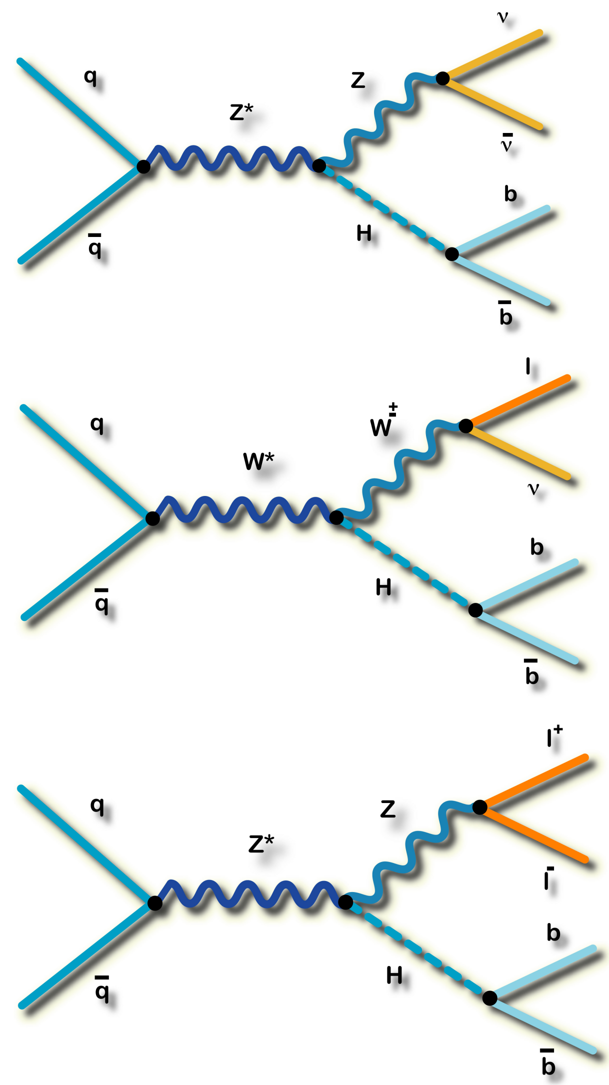
- Basic event selection : two high p_T leptons and large missing E_T ($H \rightarrow WW \rightarrow l\nu l\nu$)
  - Maximizing detector lepton acceptance is critical
- Also consider potential tri-lepton and same-sign lepton events from $WH \rightarrow WWW$ and $ZH \rightarrow ZWW$
- For $m_H = 165$ GeV/c^2, we expect to reconstruct a bit more than 7 events per fb^{-1} per experiment





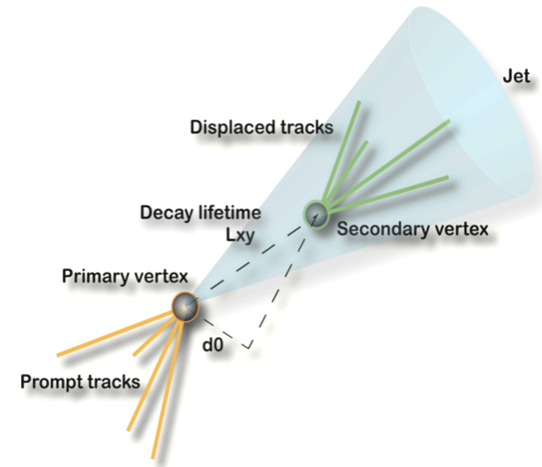
Low Mass Searches

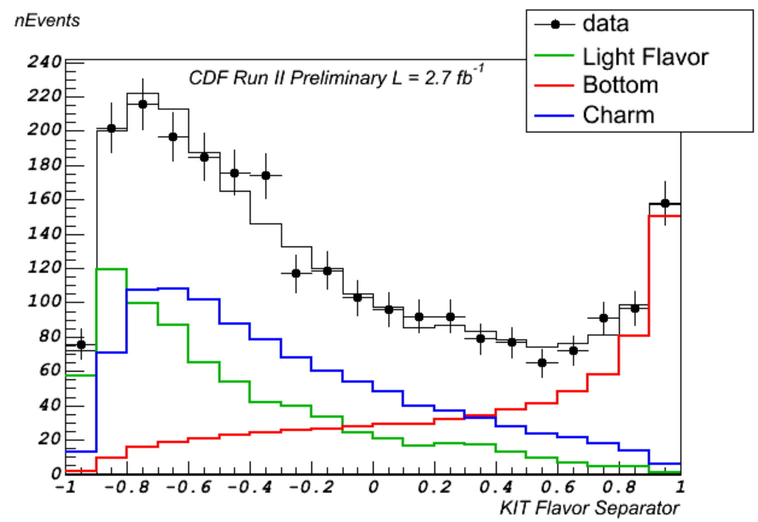
- Basic event selection : at least two reconstructed jets (b-quark candidates) plus either
  - no leptons and missing E_T ($Z \rightarrow \nu\nu$)
  - one lepton and missing E_T ($W \rightarrow l\nu$)
  - two leptons ($Z \rightarrow ll$)
- Efficiency for tagging b-quark jets is critical (as well as rate for mis-tagging light quark jets)
- For m_H = 115 GeV/c^2, we expect to reconstruct about 3.5 events per fb^{-1} per experiment (double b-tags)



Tagging Jets from b-quarks

- Idea is to pick out jets that are consistent with having originated from long-lived b-quark (typically involves reconstruction of secondary track vertex within jet)
- More sophisticated tools incorporating both jet shape and track variables are used to obtain additional discrimination between different flavor quark jets

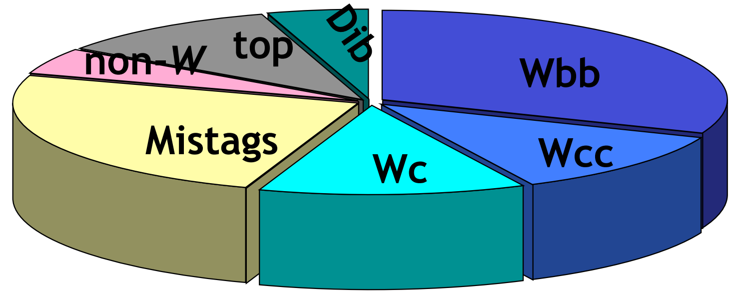




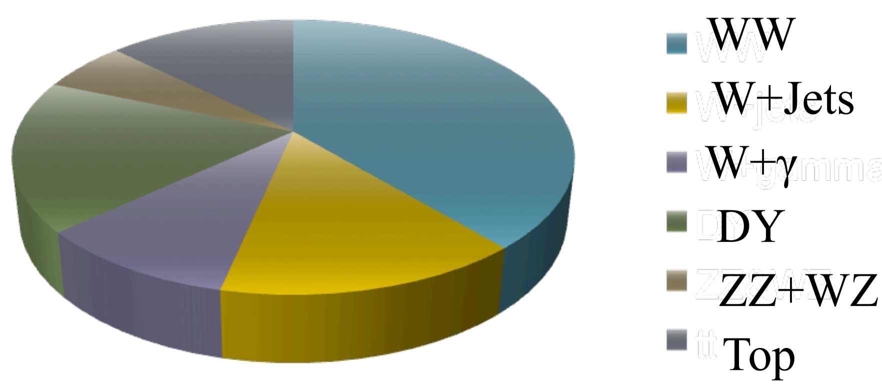
Backgrounds

- Next step is to separate small potential signal from large SM background contributions in our search channels
- For example, applying no additional selection criteria
  - S/B = 0.014 in most sensitive WH→lνbb (low-mass) search channel
  - S/B = 0.015 in most sensitive H→WW→lνlν (high-mass) search channel

$WH \rightarrow l\nu b\bar{b}$



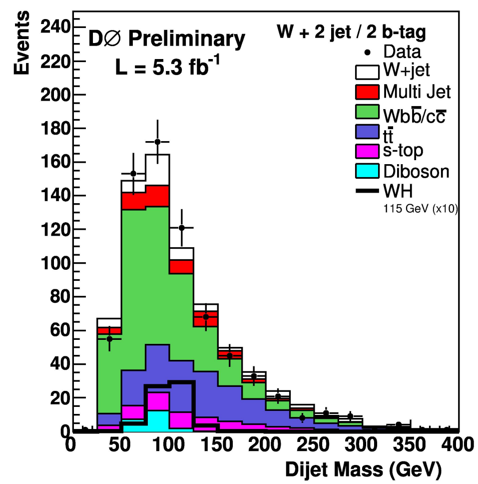
$H \rightarrow WW \rightarrow l\nu l\nu$



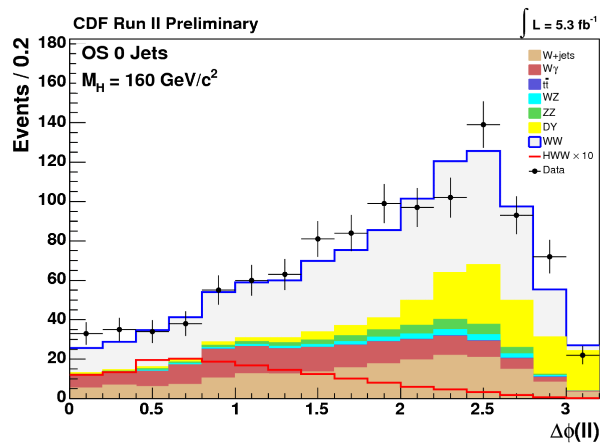
Improving S/B

- In order to improve S/B need to use kinematic information from the events
- Multi-variant techniques are used to maximize search sensitivities
  - Neural Networks
  - Boosted Decision Trees
  - Matrix Element Calculations
- Typically add only about 10-20% in sensitivity beyond that obtained using best one or two variables

WH→lνbb



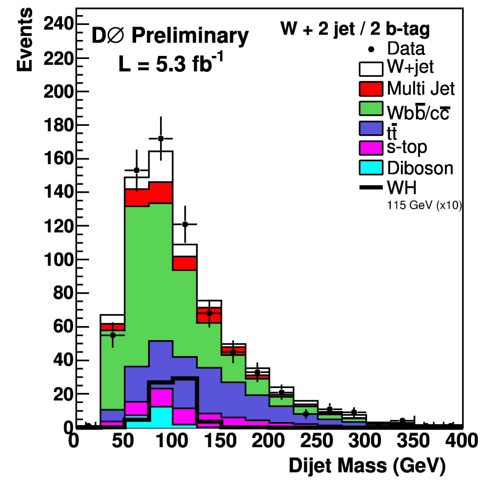
H→WW→lνlν



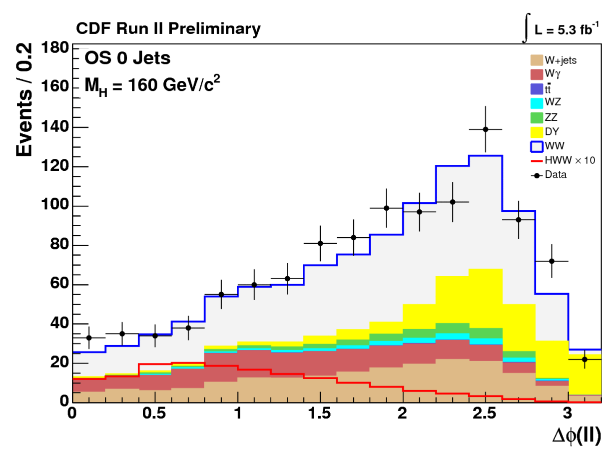
Background Modeling

- Since we rely on kinematic shapes to separate potential signal from backgrounds, the single most important aspect of these searches is how well we can model (and determine uncertainties on) these shapes
- Low mass:
  - Focus on jet E_T and angular distributions → M_{jj}
- High mass:
  - Focus on system boost (p_T) and spin information → $\Delta\phi_{ll}$

WH→lνbb

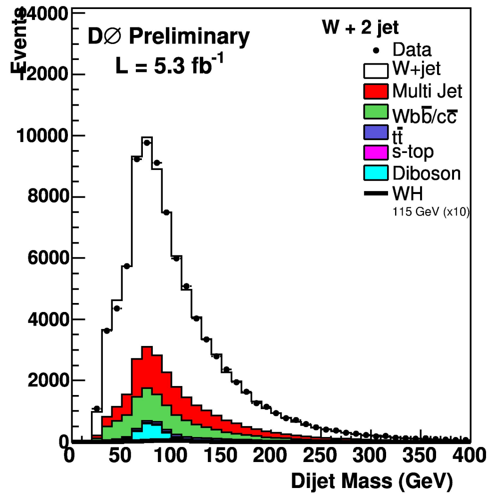


H→WW→lνlν



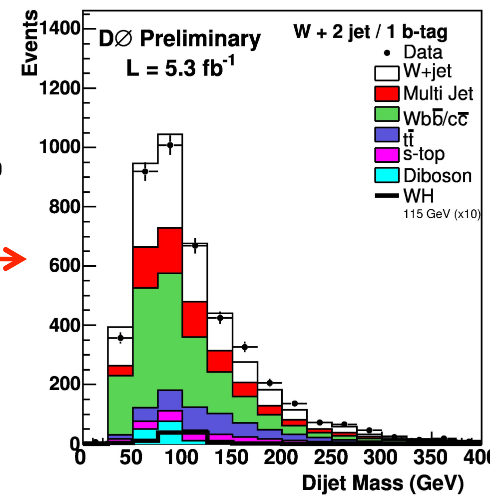
Validating Background Models

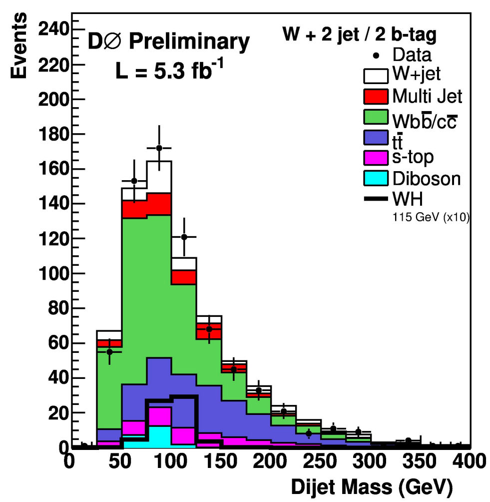
- For low mass searches, the background modeling is validated using pre-tagged and tagged event samples
  - Provide very different mix of heavy and light flavor quark production processes
- Also, measure SM cross sections for rare processes contributing events to the low mass search final state (e.g. single-top and semi-hadronic diboson decays)



No Tags

One Tag

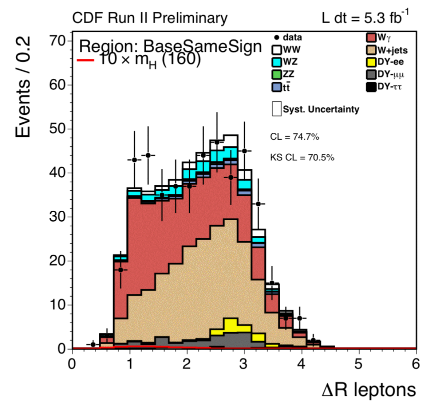




Two Tags

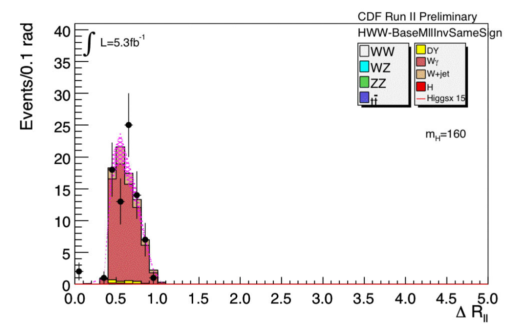
Validating Background Models

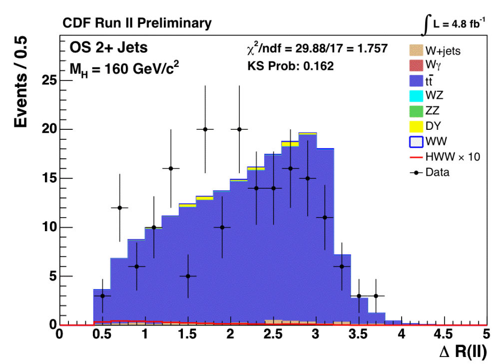
- For high mass searches, specific control regions are defined to test modeling for each individual background (whenever possible)
- In the case of dibosons (WW, WZ, and ZZ), we are not able to define specific control regions so we use cross section measurements to validate the modeling of these processes



W+jets : same-sign dileptons

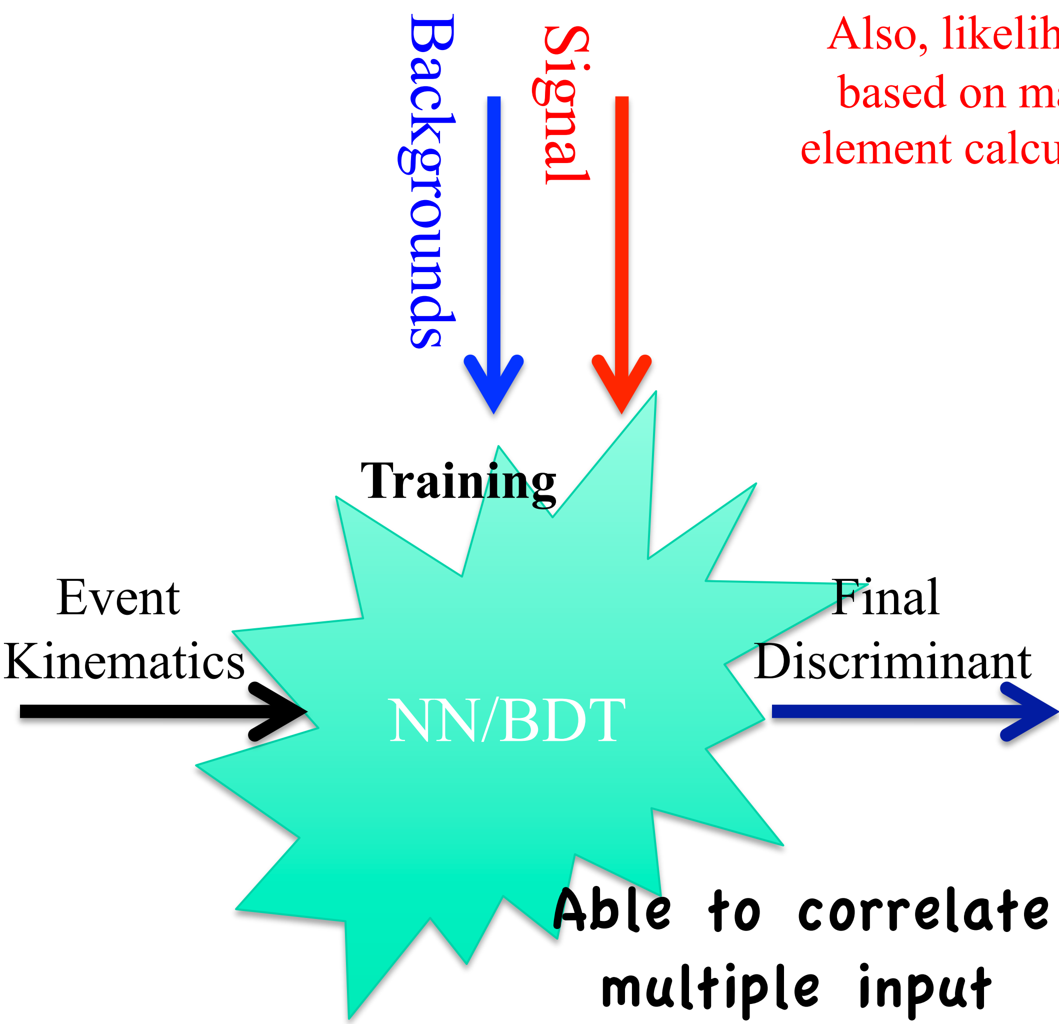
W+γ : same-sign dileptons (low M_{ll})



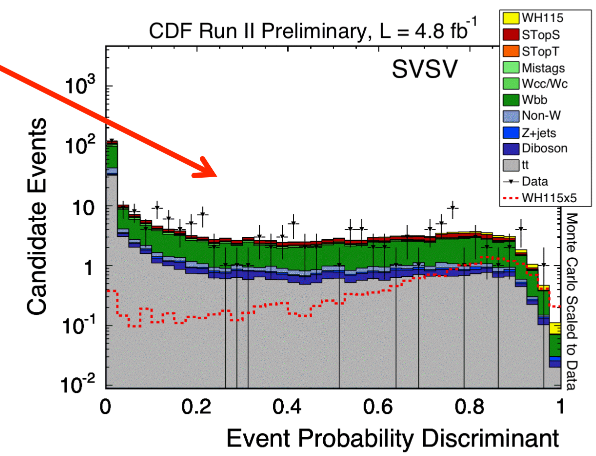


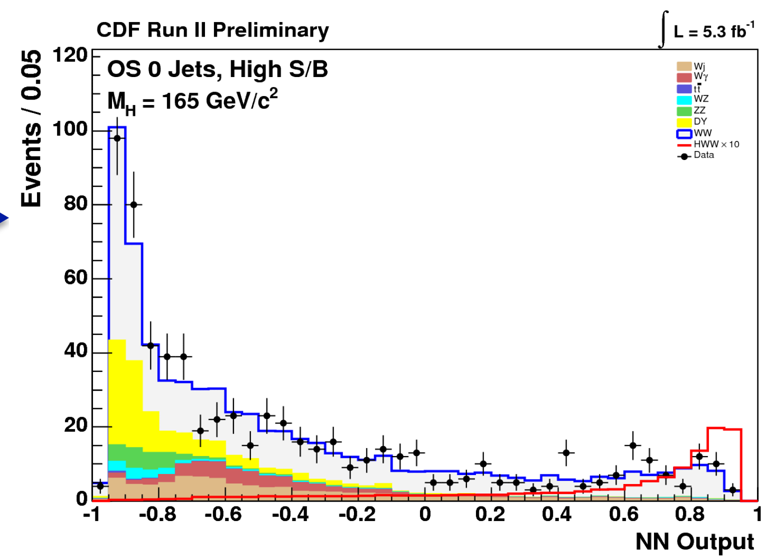
t-tbar : opposite-sign dileptons, 2+ jets, b-tag

Final Discriminates



Also, likelihoods based on matrix element calculations

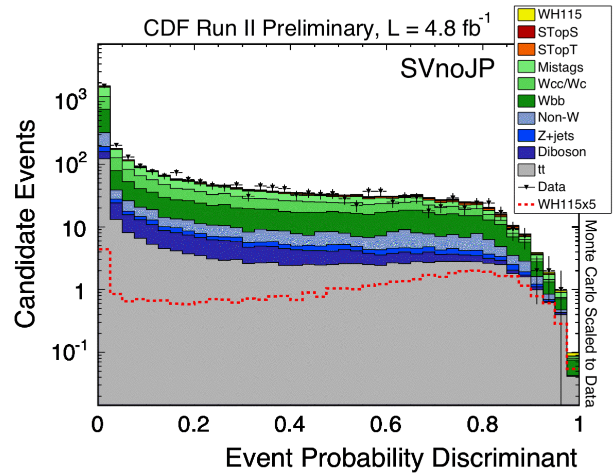


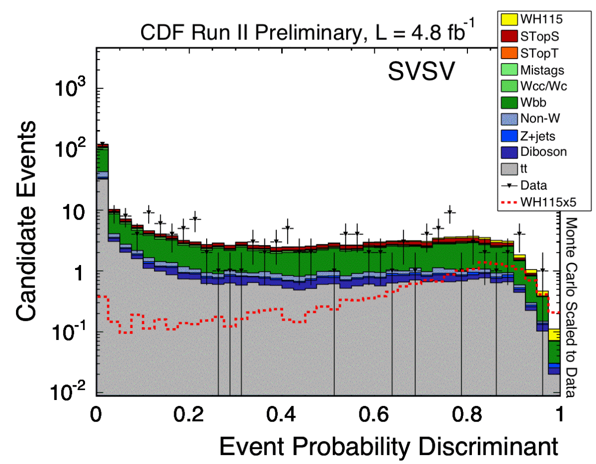


Able to correlate multiple input variables

Maximizing Sensitivity

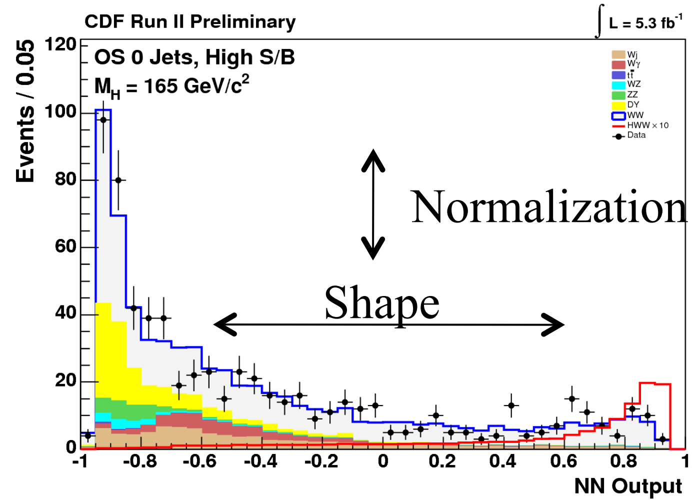
- In order to maximize the sensitivity of our searches, we need to separate events into multiple analysis channels
- We can then utilize separate, optimized discriminates for each channel tuned for
  - specific signal contributions
  - specific background contributions
  - specific event kinematics
- For low mass searches, typically define channels based on the number and quality of b-tags

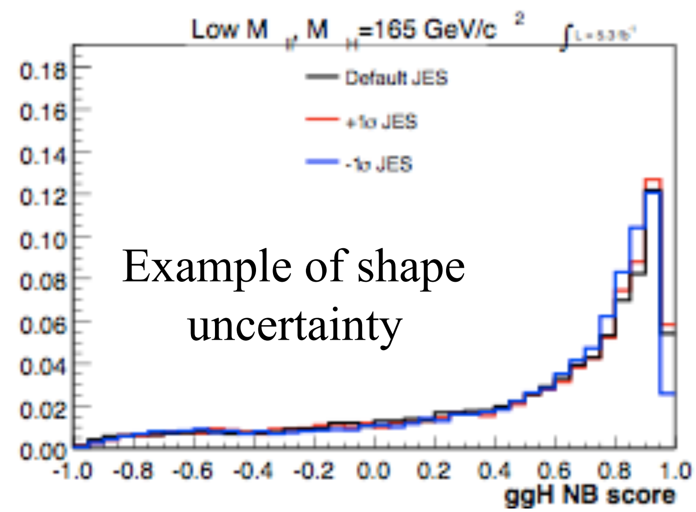




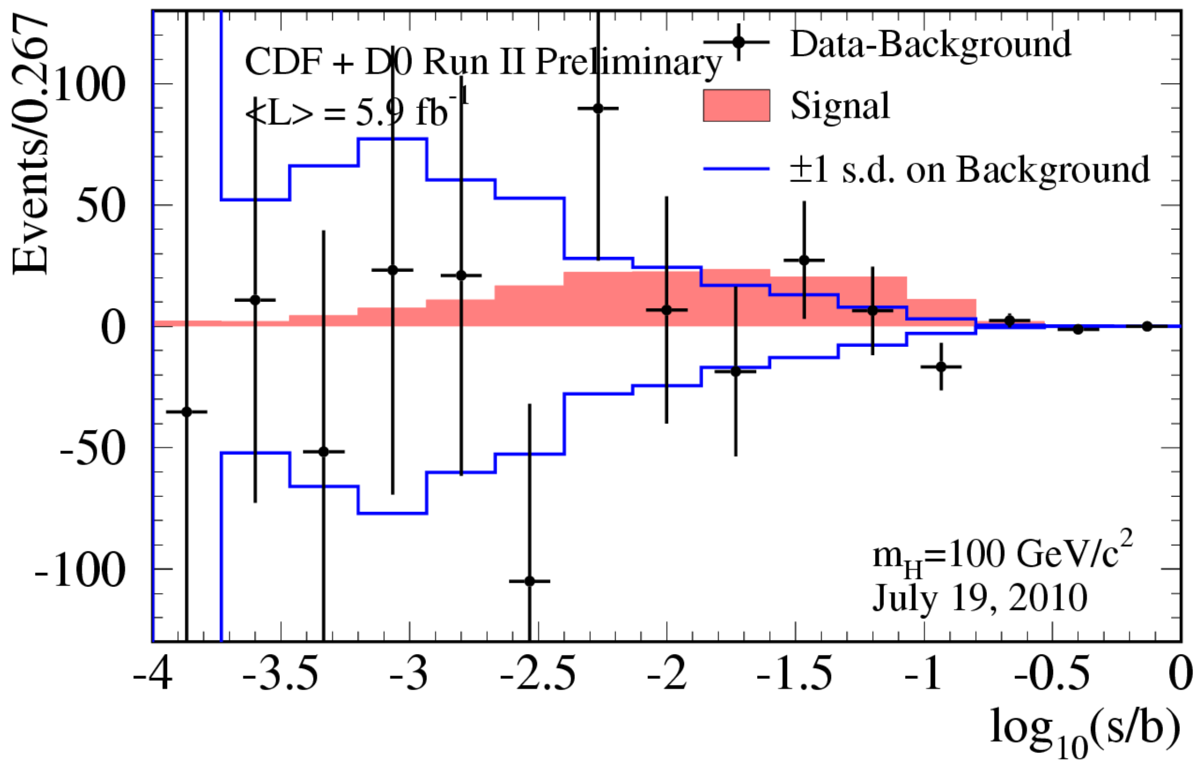
Systematic Uncertainties

- We consider uncertainties both on the overall normalization of each signal/background process and on the shapes of the final discriminant templates for each signal/background process
- Correlations in uncertainties between different channels are properly accounted for in the minimization procedure
  - A single channel can constrain an individual uncertainty parameter across all channels





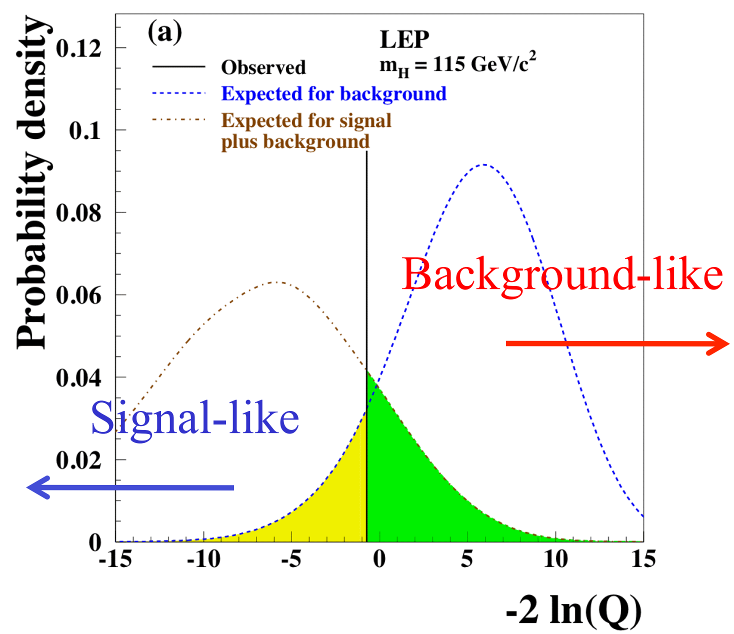
Combining Channels



Setting Limits

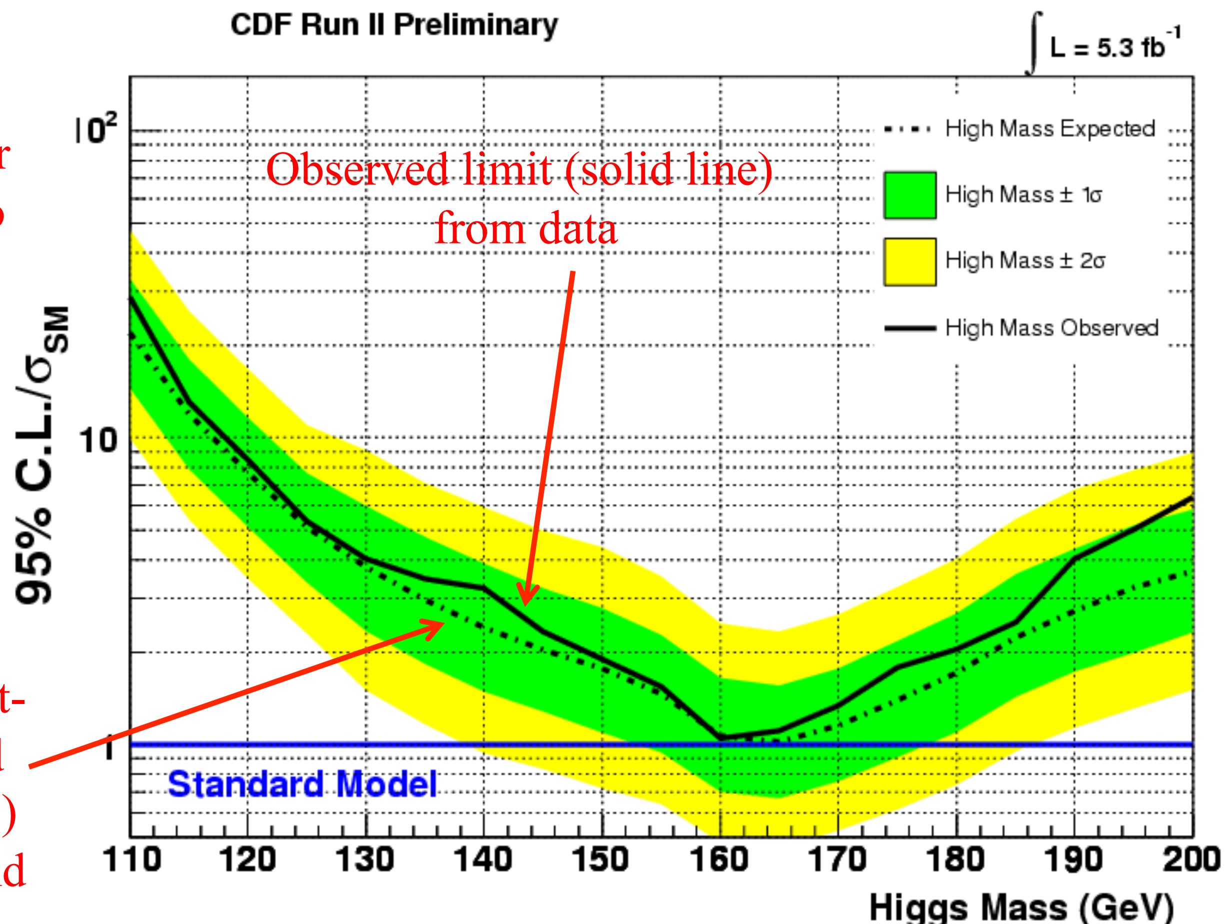
- Describe CL_S method here (Bayesian approach also used for limit setting)
- First form likelihood functions for signal plus background and background only hypotheses
  - Product over individual likelihoods for each bin in the final discriminant distributions for all channels
  - Incorporate systematic uncertainties as nuisance parameters in each term
- Maximize likelihood functions and in the process fit for both signal/background contributions and nuisance parameters
- Use pseudo-experiments to determine consistency of observed LLR with signal

$$-2\ln Q \equiv LLR \equiv -2\ln\left(\frac{L(\text{data}\,|\,s+b,\hat{\theta})}{L(\text{data}\,|\,b,\hat{\hat{\theta}})}\right)$$



Example Limit Plot

Upper cross section limit for Higgs production relative to SM prediction

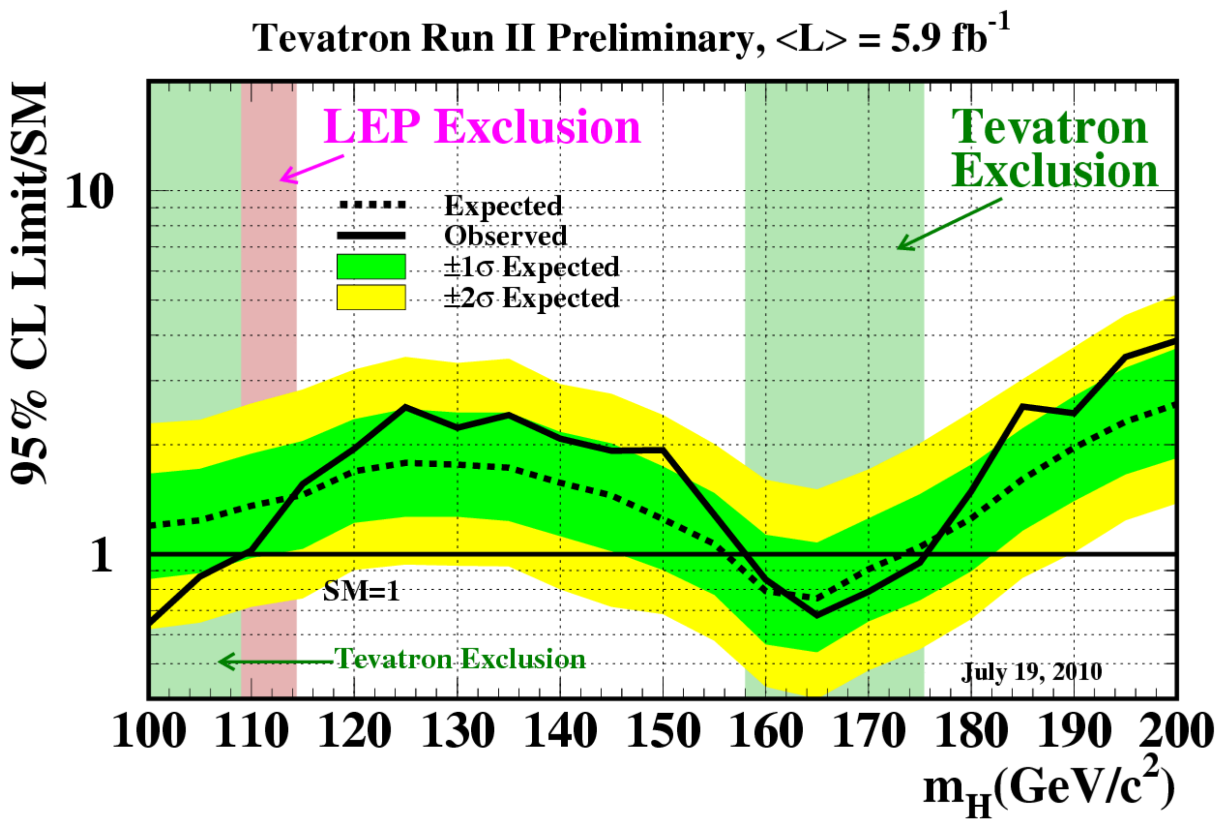


Observed limit (solid line) from data

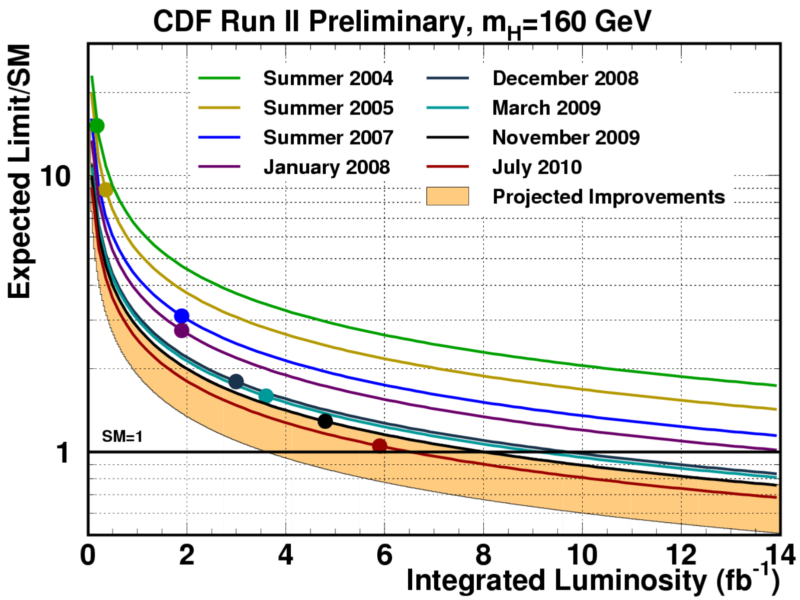
Median expected limit (dot-dashed line) and predicted 1σ/2σ (green/yellow bands) excursions from background only pseudo-experiments

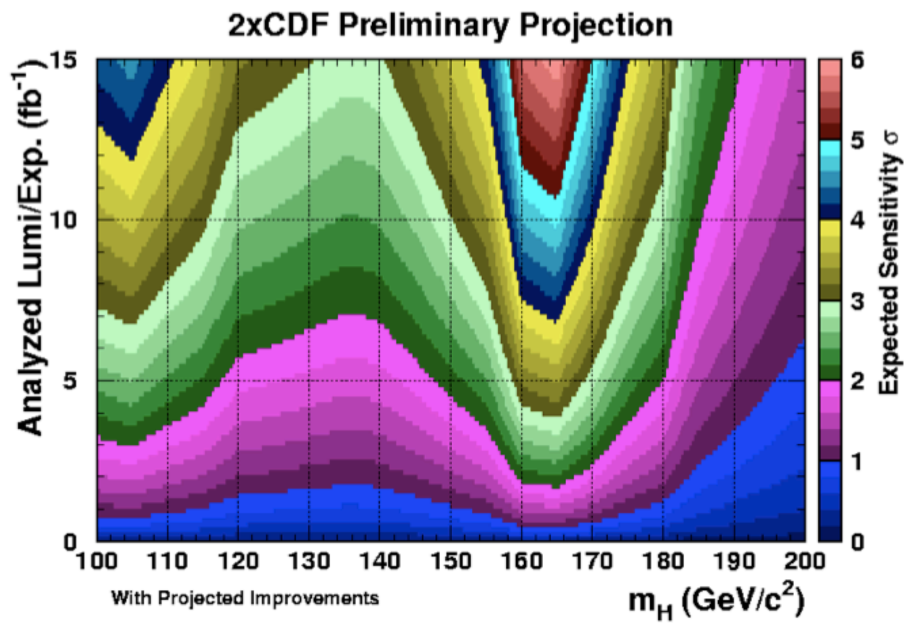
Analysis repeated using different signal templates for each m_H between 100 and 200 GeV in 5 GeV steps

Tevatron Combination



Sensitivity Projections



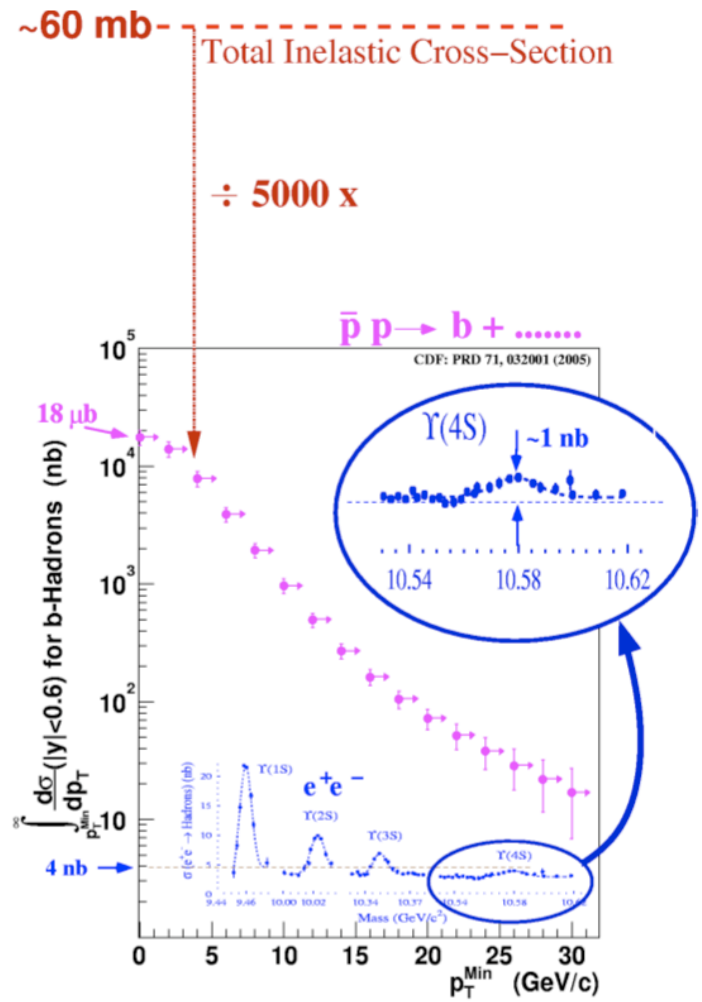


Projection of CDF expected median limit at m_H = 160 GeV versus analyzed luminosity

Median a priori expected signal excess for CDF+D0 as a function of m_H and analyzed luminosity

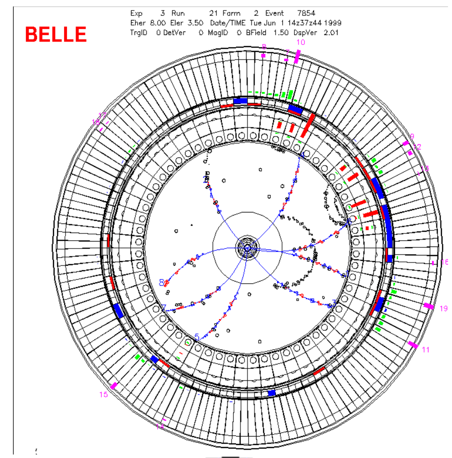
Tevatron Bottom Quark Physics

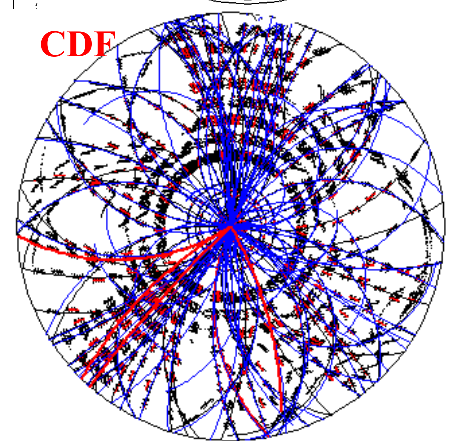
- The Good :
  - $b\bar{b}$ production cross section within detector acceptance is $O(10^3)$ above e^+e^- at $\Upsilon(4s)$
  - Incoherent strong production of all b-hadrons (B^+, B^0, B^0_s, B_c, Λ_b, Ξ_b, etc…)
- The Bad :
  - Total inelastic cross section is $O(10^3)$ above $\sigma(b\bar{b})$
  - Branching ratios of $O(10^{-6})$ for interesting processes



Tevatron Bottom Quark Physics

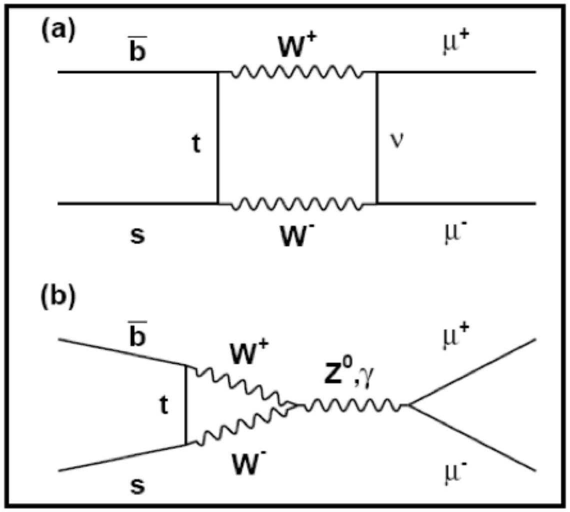
- The Ugly :
  - Messy environments with large combinatorics
  - Requires excellent tracking and selective triggering
  - Especially difficult for generic $B^0_s \rightarrow h^+h^-$ final states (displaced vertex triggers)
  - 2000 B's per second within acceptance – can't write all of these events to tape

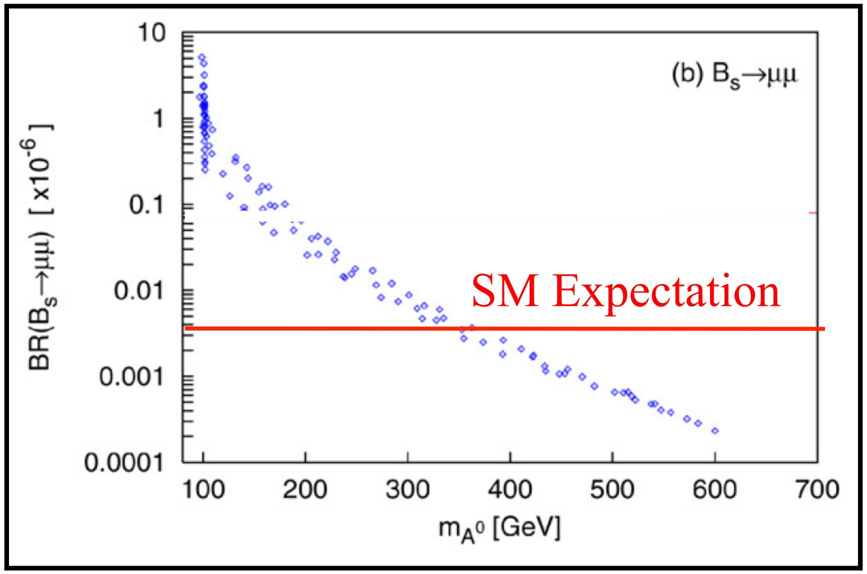




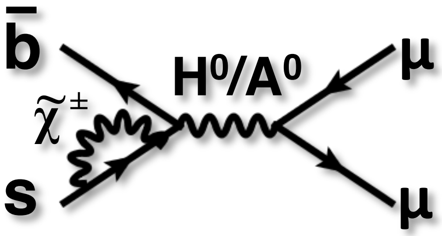
$B_{s,d} \to \mu^+\mu^-$

- Very small SM branching ratio – proceeds only via loop diagrams
- However, new physics contributions can greatly modify this expectation





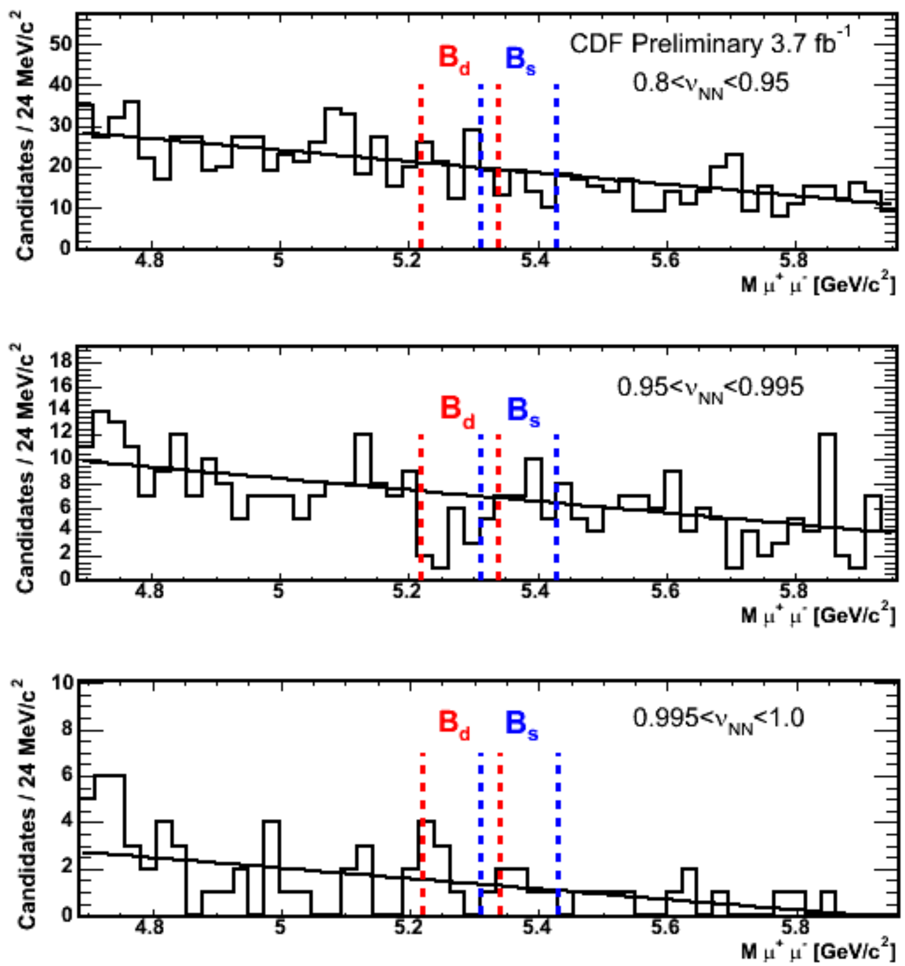
Blue dots : One particular MSSM model (J.K. Parry, Nucl. Phys. B 760, 38 (2007)



$B_{s,d} \rightarrow \mu^+\mu^-$ Results

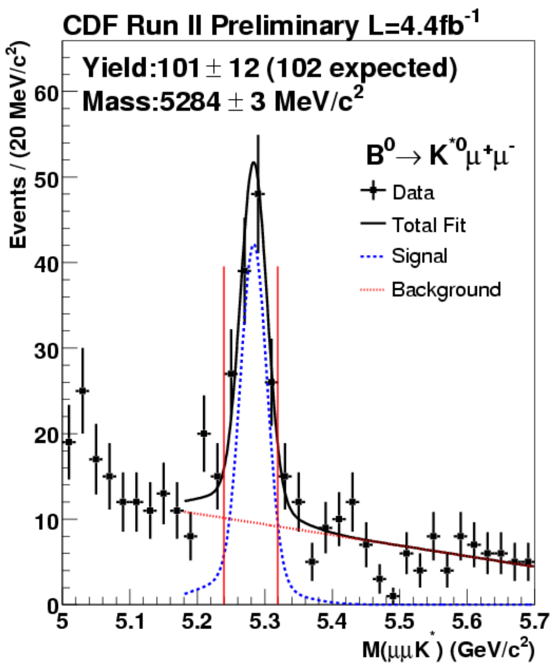
- NN variable created using various kinematic inputs to help separate signal events from background
- Limits calculated based on several bins of NN variable and reconstructed mass

$$\mathrm{Br}(B_s \rightarrow \mu^+\mu^-) < 4.3\times10^{-8}(95\%\ C.L.)$$
$$\mathrm{Expected}: 3.3\times10^{-8}(95\%\ C.L.)$$
$$\mathrm{Br}(B_d \rightarrow \mu^+\mu^-) < 7.6\times10^{-9}(95\%\ C.L.)$$
$$\mathrm{Expected}: 9.1\times10^{-9}(95\%\ C.L.)$$

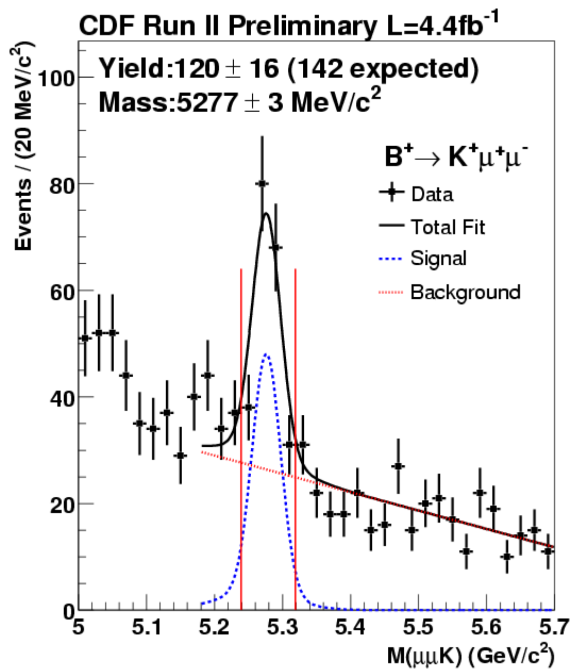


$b \rightarrow s\,\mu^+\mu^-$

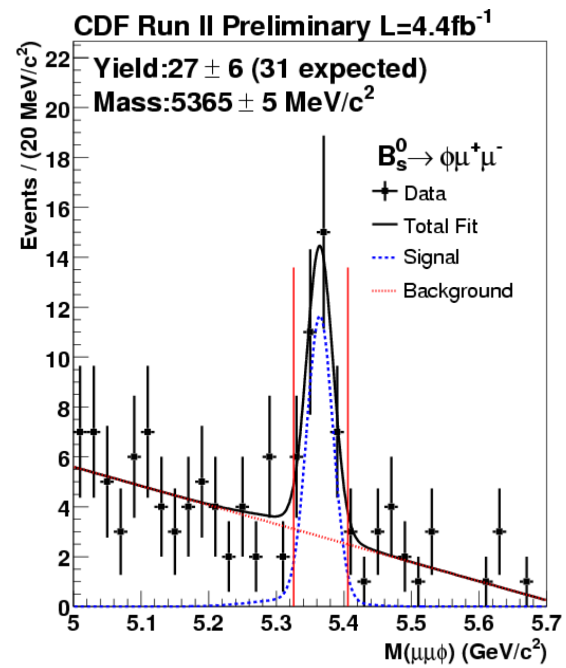
- Once again, only possible via loop diagrams in SM
- Sensitive to new physics mainly through event kinematics (A_{FB})



$B^0 \rightarrow K^{*0}(K^+\pi^-)\mu^+\mu^-$



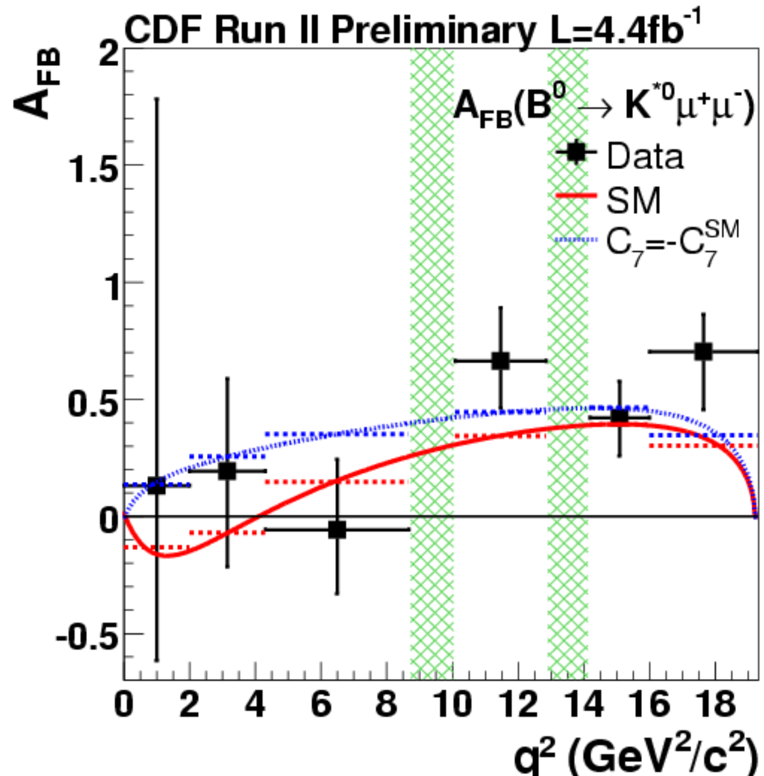
$B^+ \rightarrow K^+\mu^+\mu^-$



$B_S^0 \rightarrow \varphi(K^+K^-)\mu^+\mu^-$

$b \rightarrow s\, \mu^{+}\mu^{-}\, A_{FB}$

- In the theoretically cleanest range ($1 < q^2 < 6$ GeV^2/c^2) measured AFB is consistent and competitive with B factory measurements
- Consistent with SM prediction but discrepancy could begin to appear with additional data

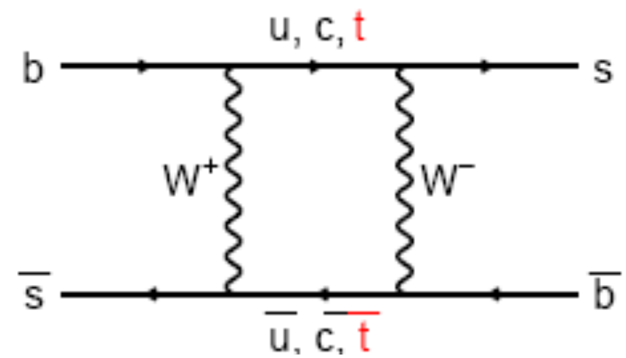


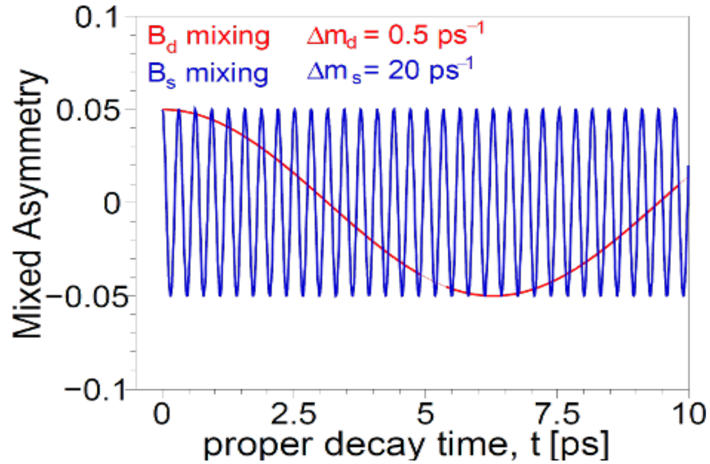
$$\boxed{A_{FB} = 0.43^{+0.36}_{-0.37} \pm 0.06\ \ (\mathrm{CDF},\ \ 1 < q^2 < 6\,\mathrm{GeV}^2)}$$

$$\boxed{A_{FB} = -0.05^{+0.03}_{-0.04}\ \ (\mathrm{SM},\ \ 1 < q^2 < 6\,\mathrm{GeV}^2)}$$ ← C. Bobeth et. al., arXiv:1006.5013

$B^0{}_S$ Mixing

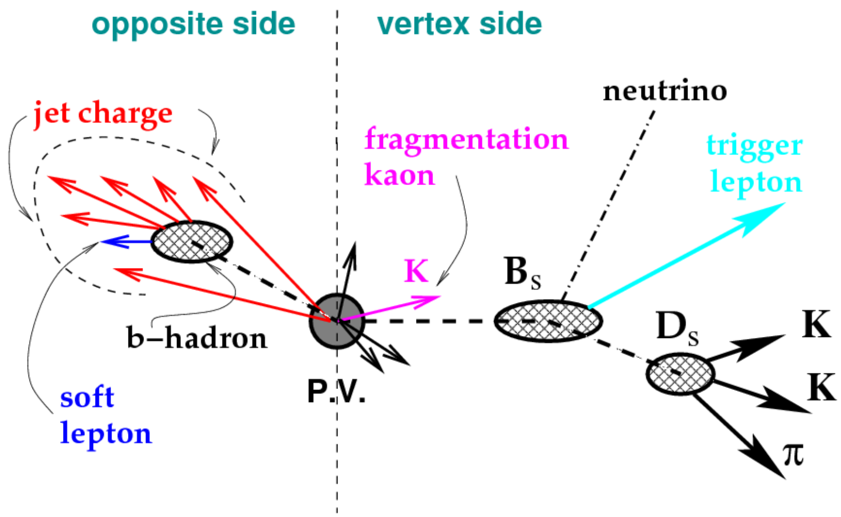
- Analogous to $B^0{}_d$ mixing but on the order of 40 times faster
- Measurement requires good proper time resolution and flavor tagging

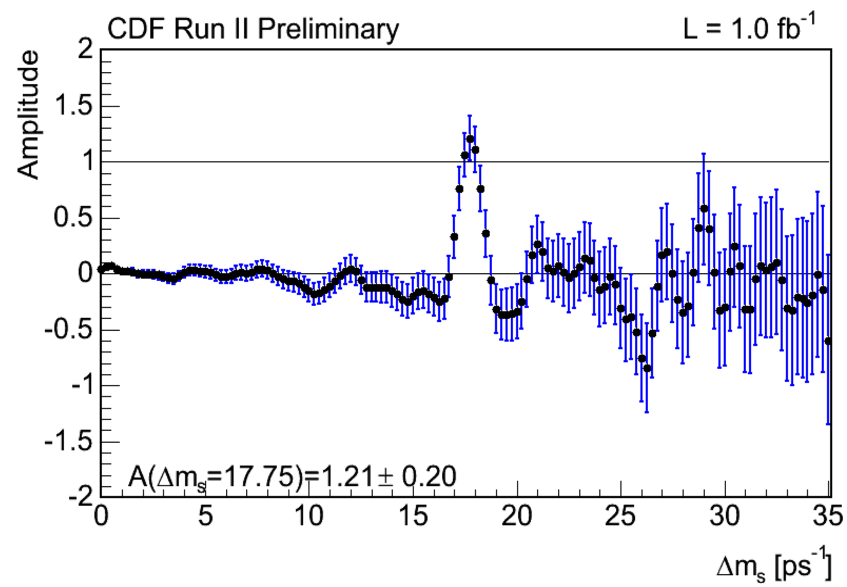




B^0_S Mixing Results

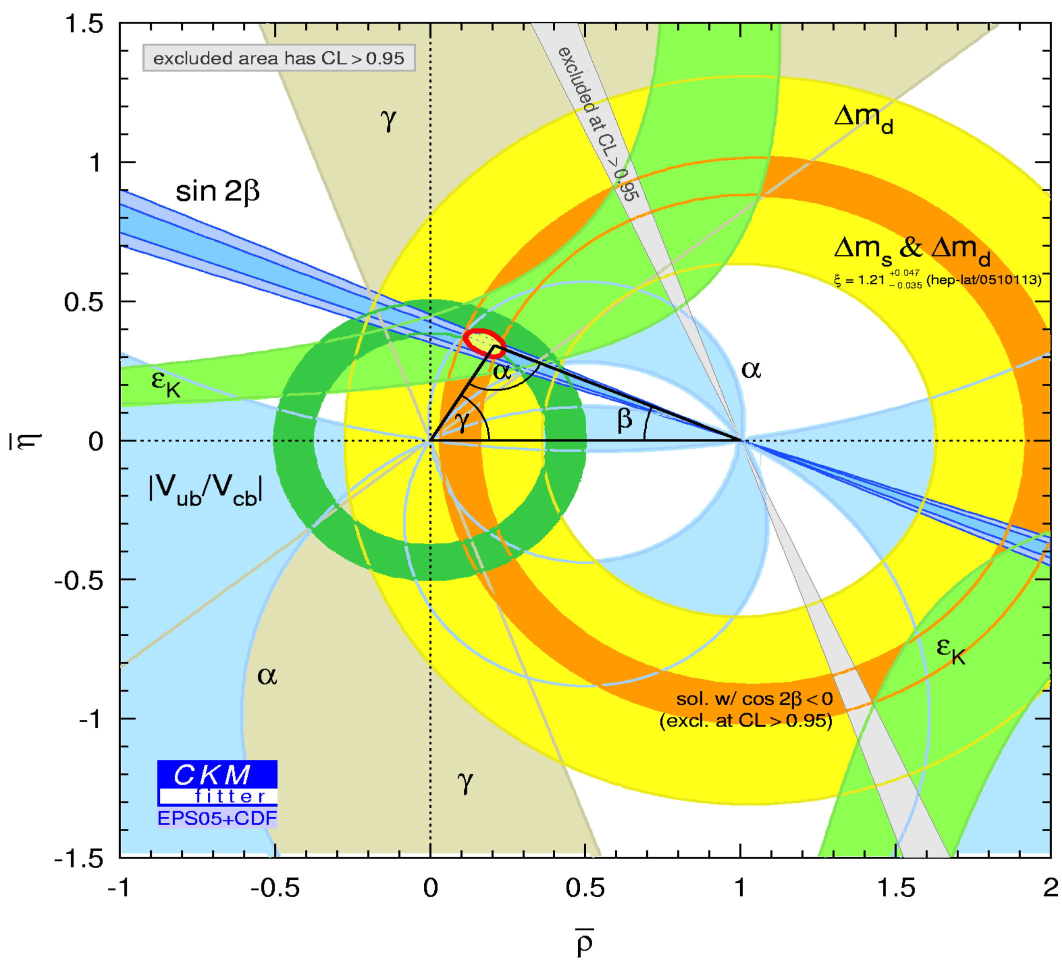
- Fully reconstruct one B^0_s decay (obtain proper lifetime and flavor at time of decay)
- Tag flavor of B^0_s at time of production using
  - Charge of opposite–side lepton
  - Charge of opposite-side jet
  - Flavor of kaon produced in hadronization of b-quark to B^0_s





B^0_S Mixing Constraints

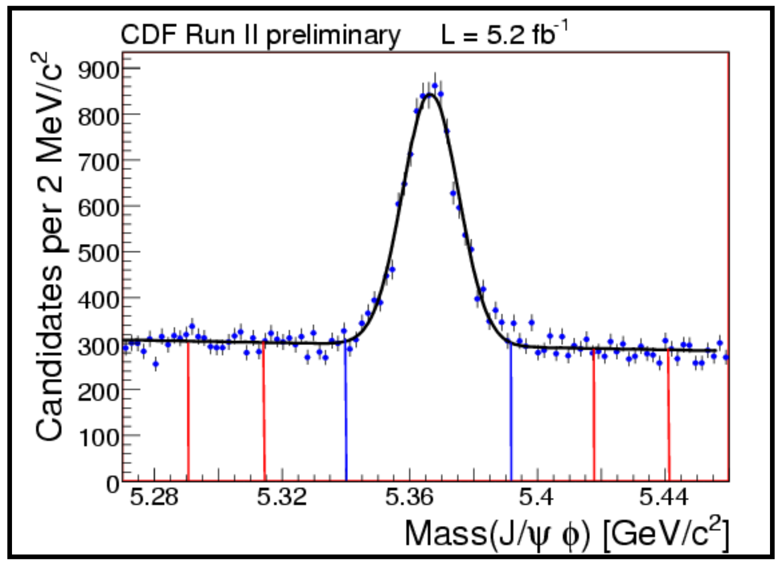
- Constrains $|V_{td}|/|V_{ts}|$ corresponding to one side of unitary triangle (indicated by orange band)
- Theory uncertainties on quantities required to extract $|V_{td}|/|V_{ts}|$ from $\Delta m_s/\Delta m_d$ much larger (~5%) than current experimental uncertainties



Probing CP Violation in $B_s \to J/\Psi\varphi$

- CP violation in $B_s \to J/\Psi\varphi$ is described by a phase which in the SM is related to the angle β_s of the unitary triangle
- Time evolution of B^0_s flavor depends on Δm_s, β_s, and $\Delta\Gamma$ between the CP even and odd eigenstates
- Using previously measured value of Δm_s simultaneously fit data for β_s and $\Delta\Gamma$

$$\phi^{J/\psi\varphi,SM} = -2\beta_s = 2\arg\left(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right)$$



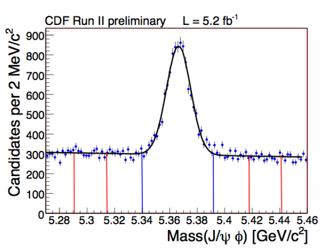
Probing CP Violation in $B_s \rightarrow J/\Psi\varphi$

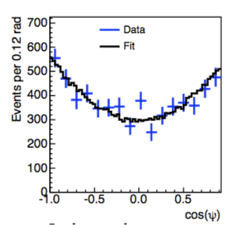
Dimuon trigger

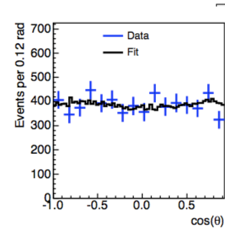
NN selection

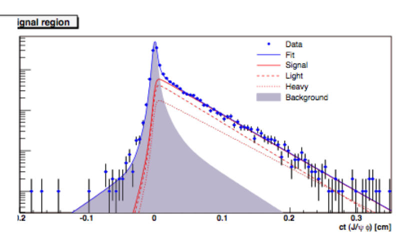
Joint fit to mass, angles, decay-time and production flavor distributions

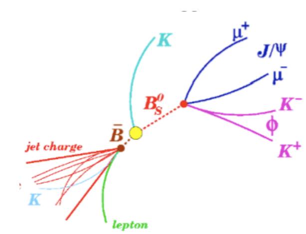
Mass to separate signal from bckg	Angles to separate CP-even/odd	Decay time to know time evolution	Flavor tagging to separate B from $\overline{B}$



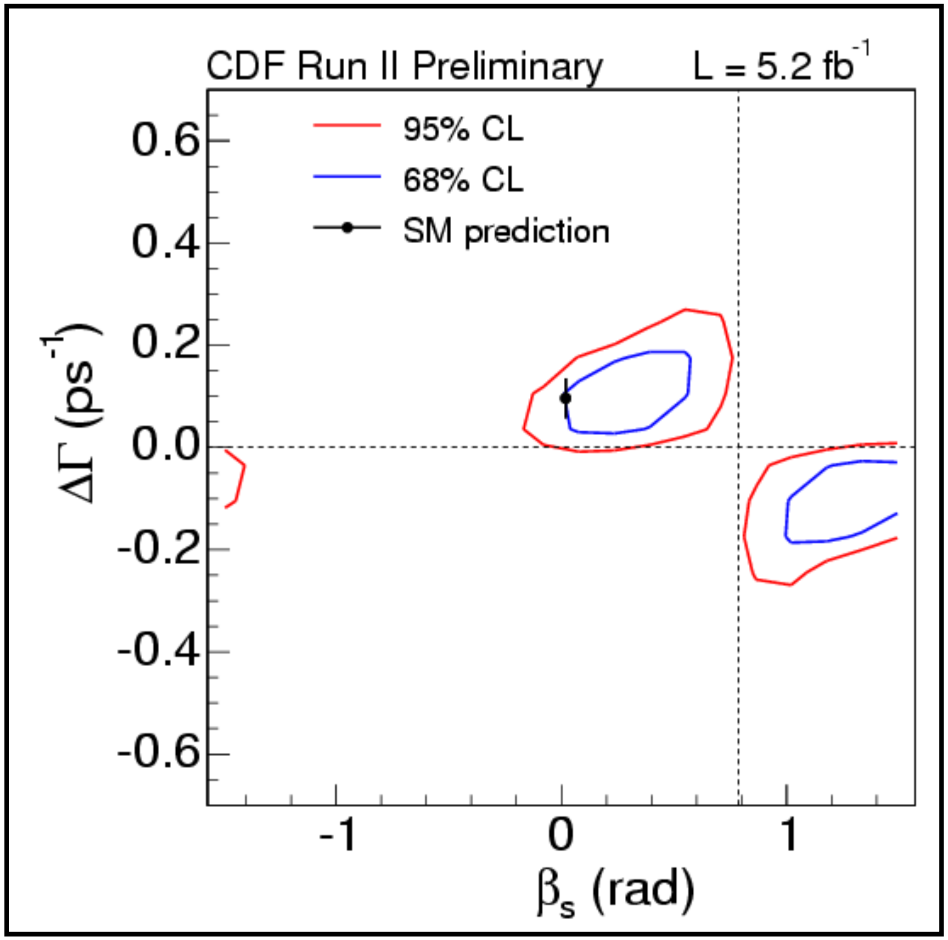








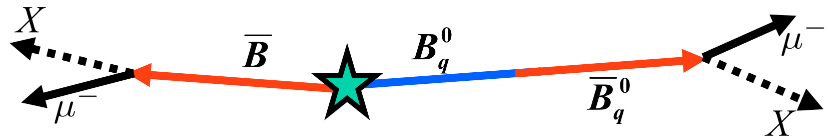
Results



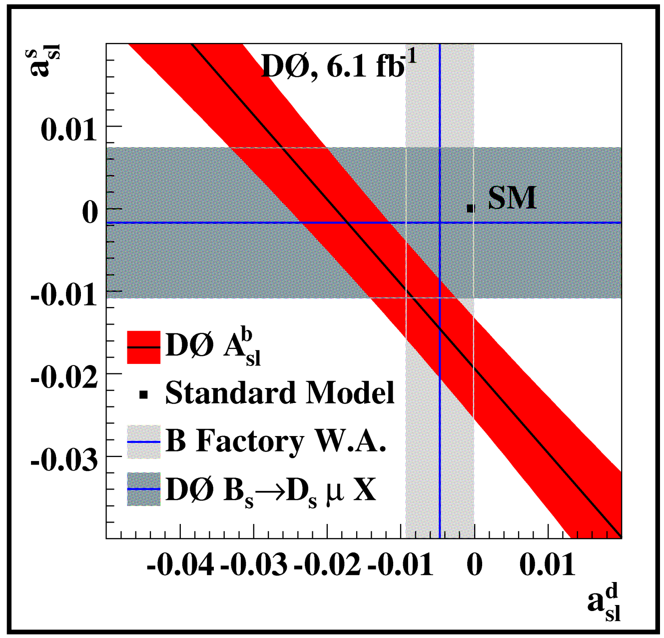
CDF Run II Preliminary
L = 5.2 fb^{-1}
95% CL
68% CL
SM prediction
$\Delta\Gamma$ (ps^{-1})
β_s (rad)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-1
0
1

Probing CP Violation in B_S Mixing

- b and $\bar{b}$ produced in equal numbers – 50% result in a neutral B meson (B^0 or B_S)
- 1.3% of the time both B mesons decay into a muon
- Two like-sign muons from $B\bar{B}$ pair implies oscillations
- $N(++) \neq N(--) \rightarrow$ CP violation
- D0 observes 3.2σ from SM

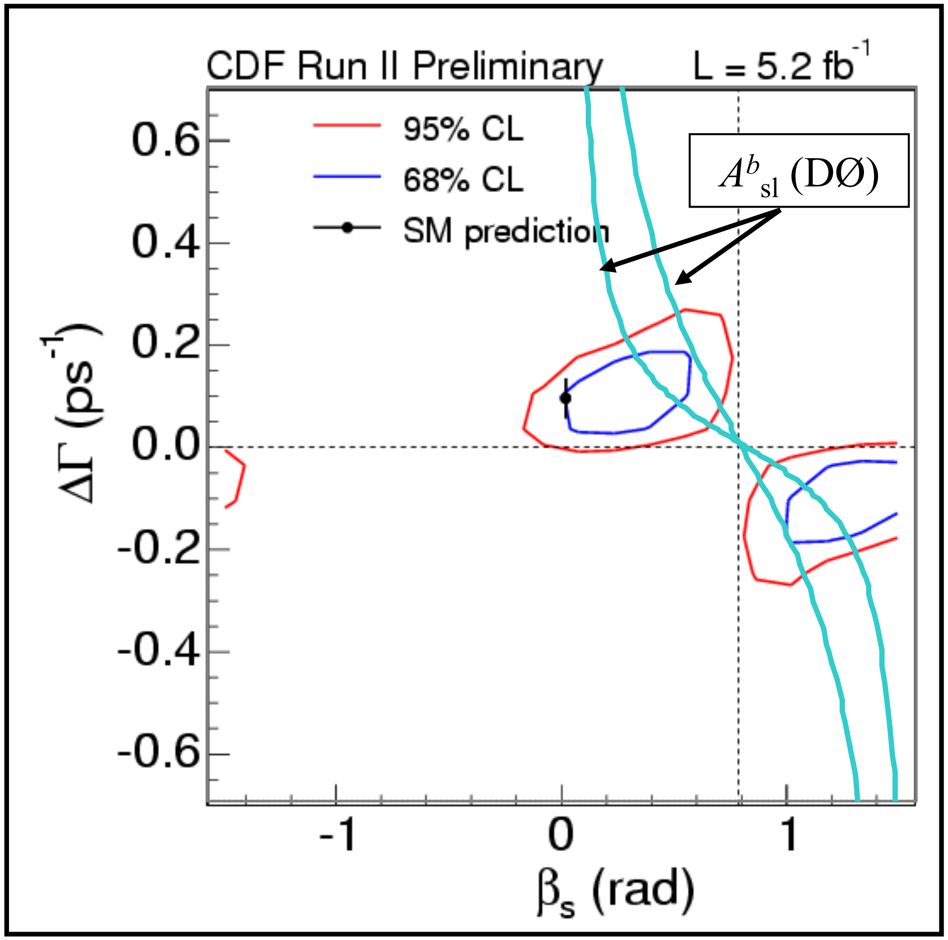


$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$



$$A_{sl}^b = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

Results



CDF Run II Preliminary
L = 5.2 fb^{-1}
95% CL
68% CL
SM prediction
A^b_{sl} (DØ)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
$\Delta\Gamma$ (ps^{-1})
-1
0
1
β_s (rad)